Precision studies at BESIII in charm and new physics search

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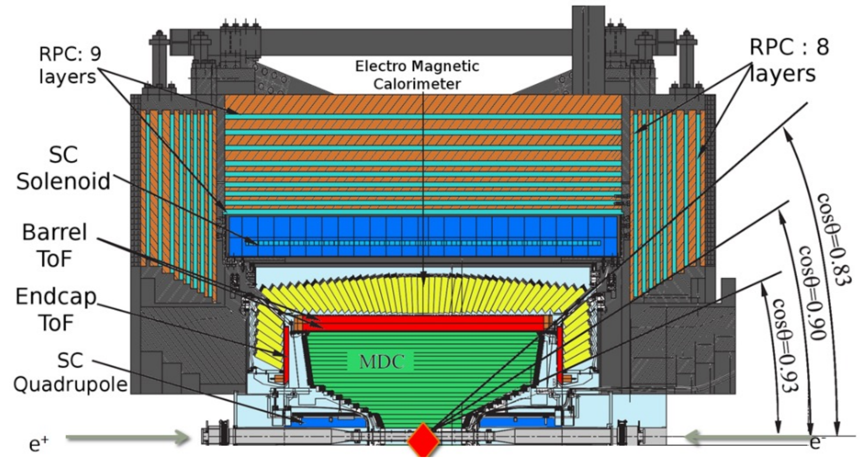
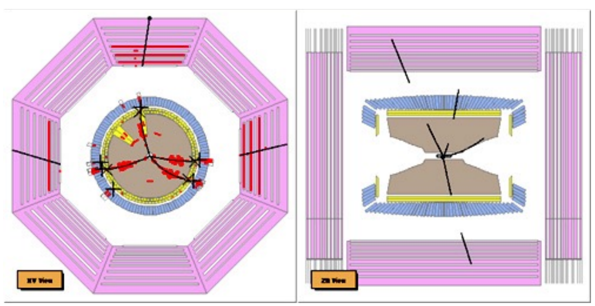
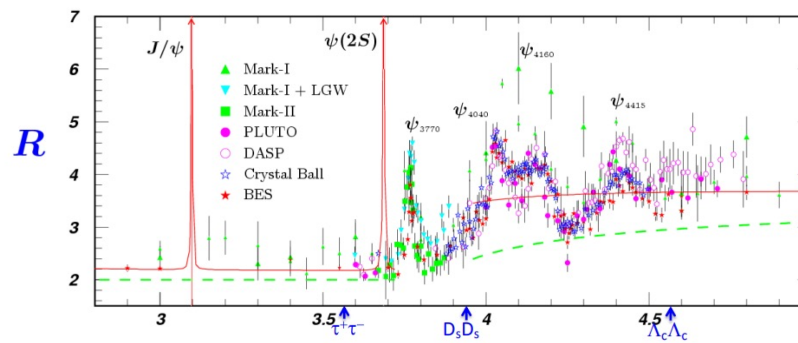
On behalf of the BESIII Collaboration

BEPCII & BESIII







First HEP collider in China (1988)
c.m.s energy： 2 ~ 5 GeV
Max luminosity： $1\times10^{33}\text{cm}^{-2}\text{s}^{-1}$

Non-perturbative
$\tau-charm$ region
$\tau^{\pm}$ 、 D/D_s、 Λ_c^+…

J/ψ： 2.97 fb^{-1}(10B)
$\psi(3686)$： 4.07 fb^{-1}(2.7B)
$\psi(3770)$： 20 fb^{-1}
4.6~4.95GeV： 6.4 fb^{-1}

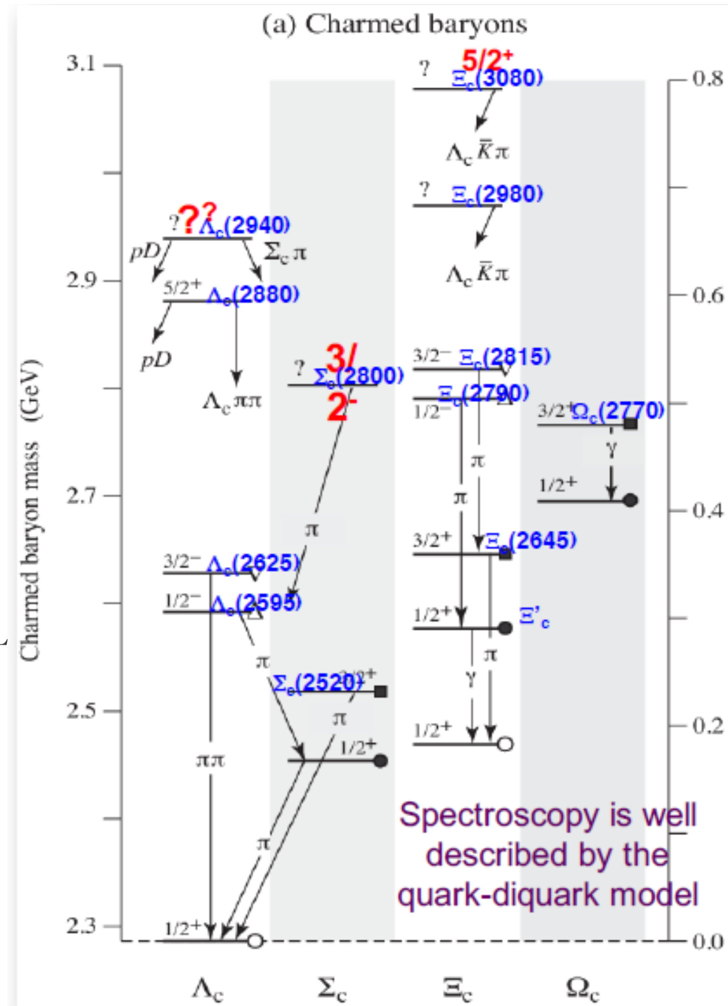
Renaissance on the charmed heavy baryon

- Before 2014, the charmed baryons have been produced and studied at many experiments, notably fixed-target experiments (such as FOCUS and SELEX) and e^+e^- B-factories (ARGUS, CLEO, BABAR, and BELLE).

- Large uncertainties in experiment=>Retarder development in theory.

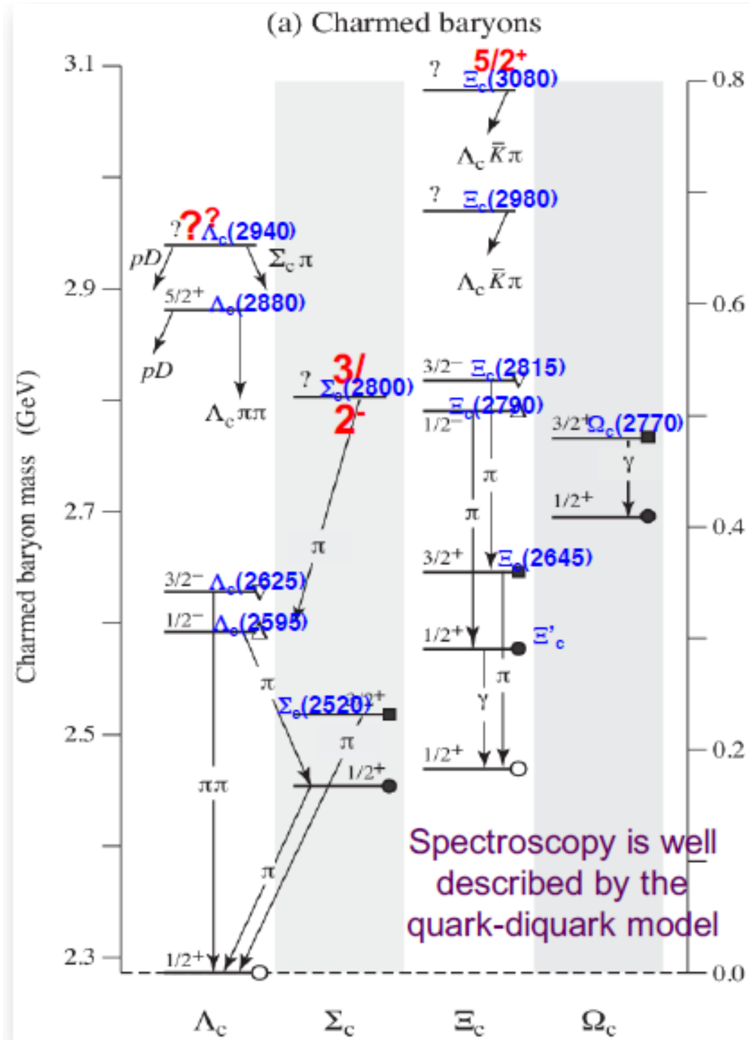
- Afterwards, more extensive measurements on charmed baryons are performed at BESIII, BELLE and LHCb.
  - The absolute BF measurements of $\Lambda_c^+ \to pK^-\pi^+$ at BESIII and BELL
  - The observation of the DCS mode $\Lambda_c^+ \to pK^+\pi^-$ at BELLE.
  - The observation of the doubly charmed baryon Ξ_{cc}^{++} at LHCb.

- These experimental progresses have revoked the activities in the theoretical efforts.



The charmed baryon family

- Singly charmed baryons
  - Established ground states:
    $\Lambda_c^+, \Sigma_c, \Xi_c^{(\prime)}, \Omega_c$
  - Excited states are being explored
- Doubly charmed baryons(Ξ_{cc}^{++}) observed in recent year.
- No observations of triply charmed baryons.



✓ Λ_c^+ decay only weakly, many experimental progress since 2014.

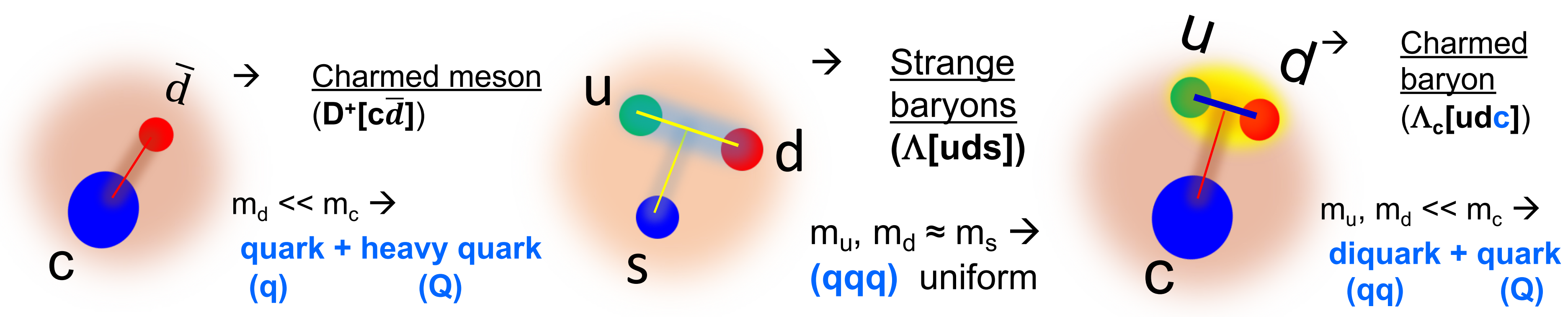
✓ Σ_c: $B(\Sigma_c \to \Lambda_c^+\pi) \sim 100\%$, $B(\Sigma_c \to \Lambda_c^+\gamma)$?

✓ Ξ_c : decay only weakly; no absolute BF measured, most relative to $\Xi^- \ \pi^+(\pi^+)$.

✓ Ω_c:decay only weakly; no absolute BF measured.

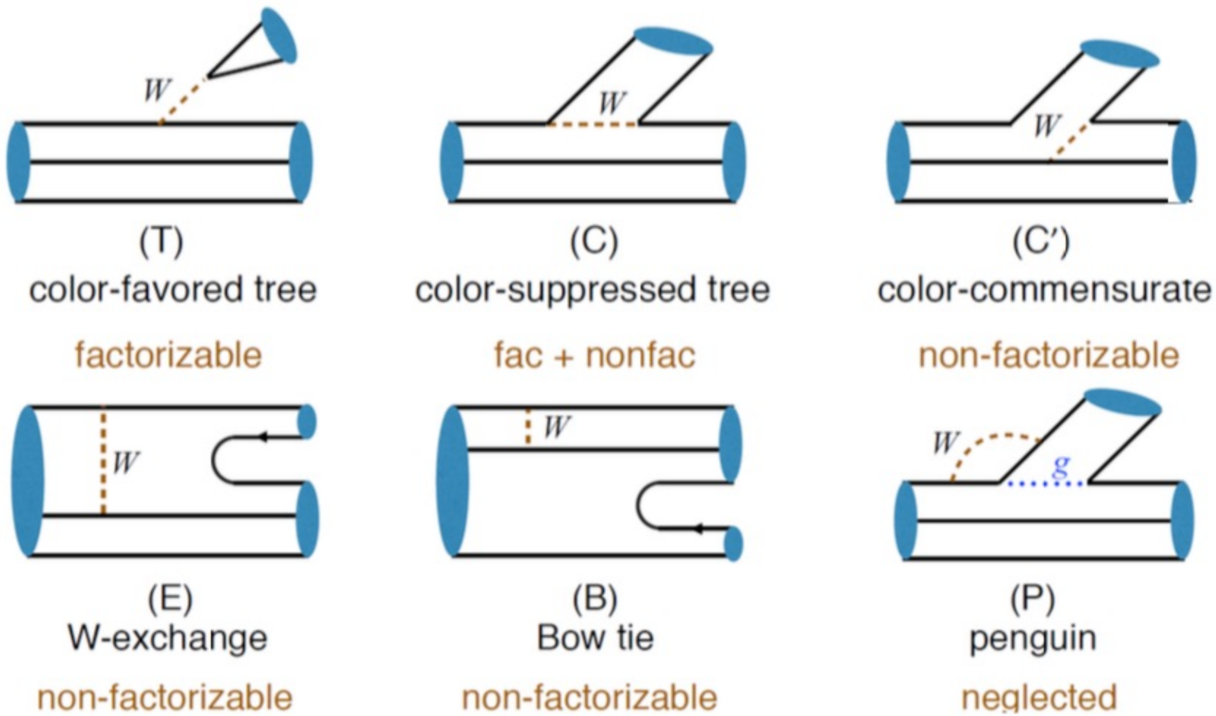
Λ_c^+: The lightest charmed baryon spectroscopy

- Most of the charmed baryons will eventually decay to Λ_c^+.
- The Λ_c^+ is one of important tagging hadrons in c-quark counting in the productions at high energy experiment.
- Naïve quark model picture: a heavy quark (c) with an unexcited spin-zero diquark (u-d). Diquark correlation is enhanced by weak Color Magnetic Interaction with a heavy quark(HQET).
- Λ_c^+ may reveal more information of strong- and weak-interactions in charm region, complementary to D/Ds



Λ_c^+ weak decay picture in theory

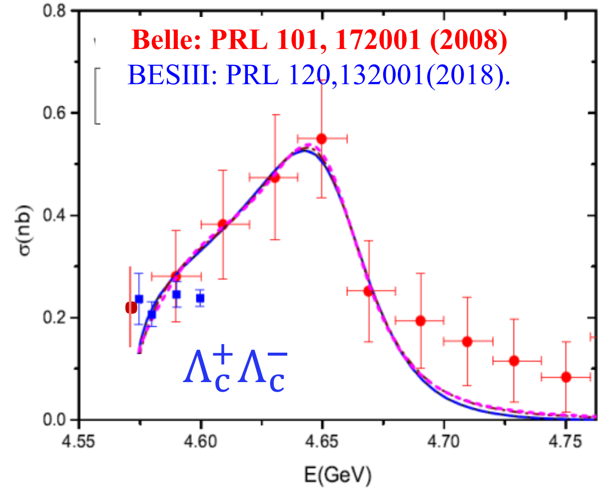
- Contrary to charmed meson, W-exchange contribution is important.(No color suppress and helicity suppress)

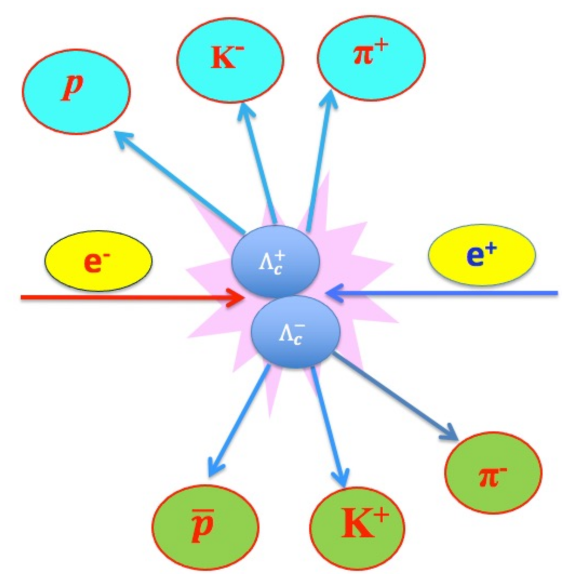


- Phenomenology aim at explain data and predict important observables.
- Calculate what they can(HQET, factorization)+parametrize what they cannot + some non-perturbations extracted from data=> explain and predict.

Production near threshold and tag technique

- E_{cms}-$2M_{\Lambda c}$=26MeV only!
- $\Lambda_c^+\Lambda_c^-$ produced in pairs with no additional accompany hadrons. $e^+e^-\to\gamma^*\to\Lambda_c^+\Lambda_c^-$
- Clean backgrounds and well constrained kinematics.
- Typically, two ways to study Λ_c^+ decays:
  - Single Tag(ST): detect only one of the $\Lambda_c^+\Lambda_c^-$.
    =>Relative higher backgrounds
    =>Higher efficiencies
    =>Full reconstruction only
  - Double Tag(DT): detect both of $\Lambda_c^+\Lambda_c^-$
    =>Lower backgrounds.
    =>Technique for missing particle.
    =>Systematic in tag side are mostly cancelled.

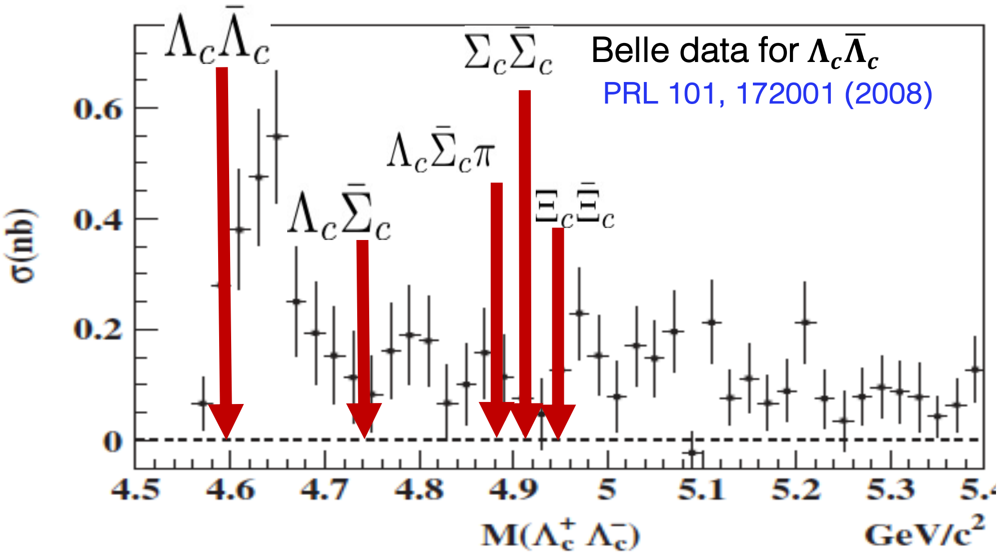




New data samples in 2020 and 2021

Two major changes in BEPCII machine:

- **max beam energy: 2.30➔2.35(2020)➔ 2.48 GeV(2021)**
- **top-up injection:** data taking efficiency increased by 20~30%



CPC46.113003(2022)

Sample	E_{cms}/MeV	$\mathscr{L}_{Bhabha}$/pb^{-1}
4610	4611.86±0.12±0.30	103.65±0.05±0.55
4620	4628.00±0.06±0.32	521.53±0.11±2.76
4640	4640.91±0.06±0.38	551.65±0.12±2.92
4660	4661.24±0.06±0.29	529.43±0.12±2.81
4680	4681.92±0.08±0.29	1667.39±0.21±8.84
4700	4698.82±0.10±0.36	535.54±0.12±2.84
4740	4739.70±0.20±0.30	163.87±0.07±0.87
4750	4750.05±0.12±0.29	366.55±0.10±1.94
4780	4780.54±0.12±0.30	511.47±0.12±2.71
4840	4843.07±0.20±0.31	525.16±0.12±2.78
4920	4918.02±0.34±0.34	207.82±0.08±1.10
4950	4950.93±0.36±0.38	159.28±0.07±0.84

Available data for charmed baryons

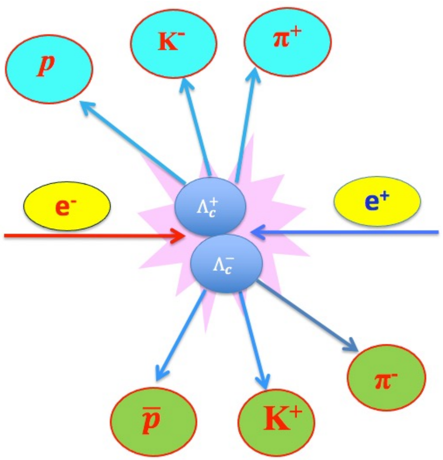
- ✓ 0.567 fb^{-1} at 4.6 GeV (35 days in 2014)
- ✓ 3.9 fb^{-1} scan at 4.61, 4.63, 4.64, 4.66, 4.68, 4.7 GeV (186 days in 2020)
- ✓ 1.93 fb^{-1} scan at 4.74, 4.75, 4.78, 4.84, 4.92, 4.95 GeV (99 days in 2021)
- 8x Λ_c data that those at 4.6GeV.(~0.77M $\Lambda_c^+\bar{\Lambda}_c^-$)
- accessible to $\Sigma_c/\Xi_c/\Lambda_c^*$ prod. & decays

Production measurement near threshold

PhysRevLett.131.191901(2023)

- $e^+e^- \to \Lambda_c^+ \Lambda_c^-$ cross section are measured at twelve energy points from 4.612-4.951GeV .

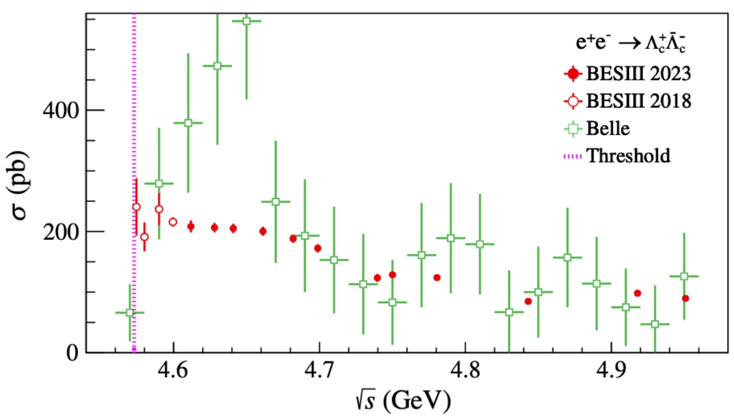
$$\sigma_{\pm} = \frac{N_{\rm ST}^{\pm}}{\varepsilon_{\rm ST}^{\pm} f_{\rm ISR} f_{\rm VP} \mathcal{L}_{\rm int} N_{\rm DT}} \sum_{n=1}^{9} \left(\frac{N_{\rm ST}^{\mp,n} \varepsilon_{\rm DT}^{n}}{\varepsilon_{\rm ST}^{\mp,n}} \right),$$

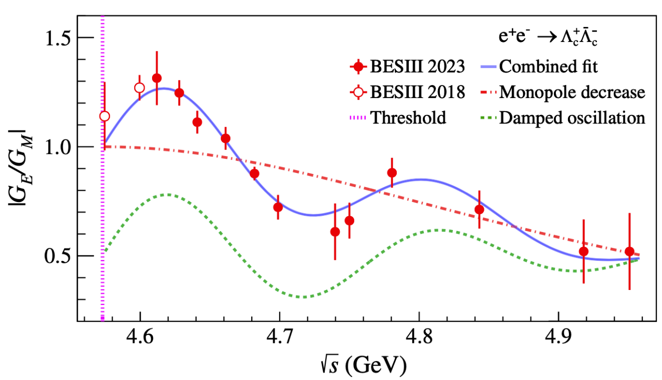


- Indicate no enhancement around Y(4630) resonance. =>Conflict with Belle.

- $|G_E/G_M|$ ratio are derived by fitting to angular distribution.

- The oscillations on $|G_E/G_M|$ ratio is significantly observed with higher frequency than that of the proton.





Recent studies on the Λ_c^+ measurments at BESIII

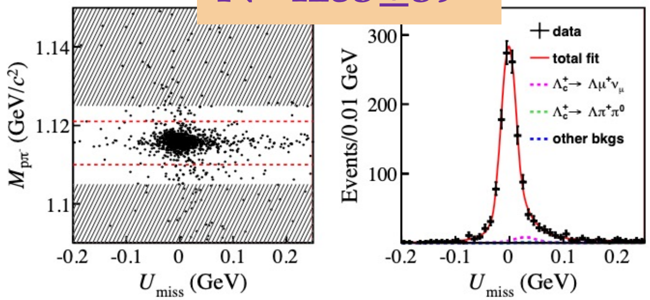
- Λ_c^+ leptonic decays
  - ☐ $\Lambda_c^+ \to \Lambda e^+\nu_e, \Lambda\mu^+\nu_\mu$ ✓ : PRL 129.231803 (2022). PRD 108.L031105 (2023).
  - ☐ $\Lambda_c^+ \to pK^-e^+\nu_e$: PRD 106.112010 (2022).
  - ☐ $\Lambda_c^+ \to Xe^+\nu_e$: PRD 107.052005 (2023).
  - ☐ $\Lambda_c^+ \to \Lambda\pi^+\pi^-e^+\nu_e,\ pK_S^0\pi^-e^+\nu_e$ ✓: PLB 843.137993 (2023).

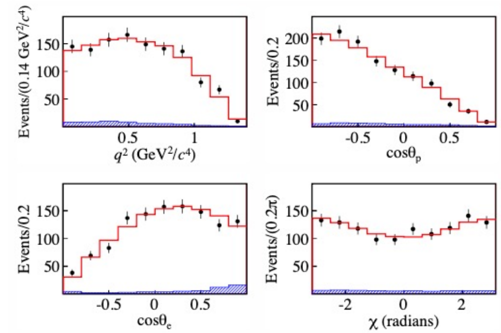
- Λ_c^+ hadronic decays(two body)
  - ☐ $\Lambda_c^+ \to n\pi^+$ ✓ : PRL 128.142001 (2022).
  - ☐ $\Lambda_c^+ \to p\eta'$: PRD 106.072002 (2022).
  - ☐ $\Lambda_c^+ \to p\eta, p\omega$: JHEP 11.137 (2023).
  - ☐ $\Lambda_c^+ \to p\pi^0, p\eta$: arXiv2311.06883.
  - ☐ $\Lambda_c^+ \to \Lambda K^+$: PRD 106.L111101 (2022).
  - ☐ $\Lambda_c^+ \to \Sigma^0 K^+, \Sigma^+ K_S^0$: PRD 106.052003 (2022).
  - ☐ $\Lambda_c^+ \to \Xi^0 K^+$ ✓ : arXiv2309.02774(PRL accepted)
- Λ_c^+ hadronic decays(multi-body)
  - ☐ $\Lambda_c^+ \to n\pi^+\pi^0$、$n\pi^+\pi^-\pi^+$、$nK^-\pi^+\pi^+$: CPC 47.023001 (2023).
  - ☐ $\Lambda_c^+ \to nK_S^0\pi^+, nK_S^0K^+$: arXiv2311.17131.
  - ☐ $\bar{\Lambda}_c^- \to \bar{n}X$ ✓ : PRD 108.L031101 (2023).
  - ☐ $\Lambda_c^+ \to \Lambda\pi^+\pi^0$ ✓ : JHEP 12.033 (2022).
  - ☐ $\Lambda_c^+ \to \Lambda K^+\pi^0, \Lambda K^+\pi^+\pi^-$: arXiv2311.12903.
  - ☐ $\Lambda_c^+ \to \Sigma^- K^+\pi^+$: arXiv2309.05484.
  - ☐ $\Lambda_c^+ \to \Xi^0 K^+\pi^0$: arXiv2311.02347.

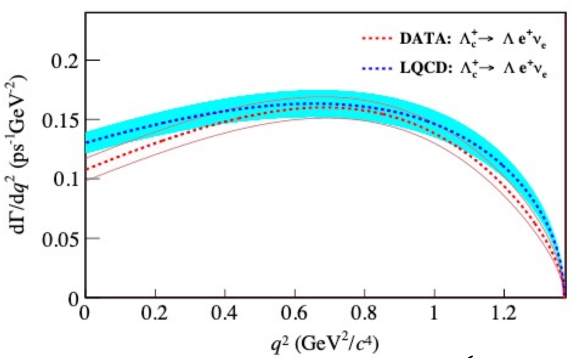
Form factors of $\Lambda_c^+ \to \Lambda e^+ \nu_e$

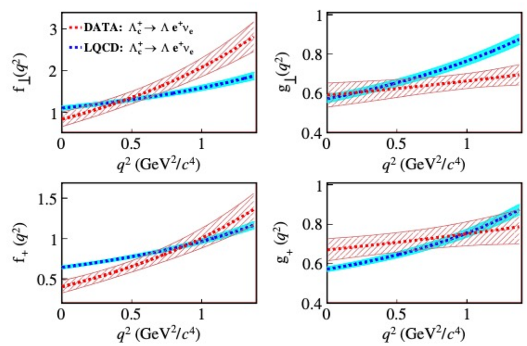
PRL 129,231803(2022)

N=1253±39



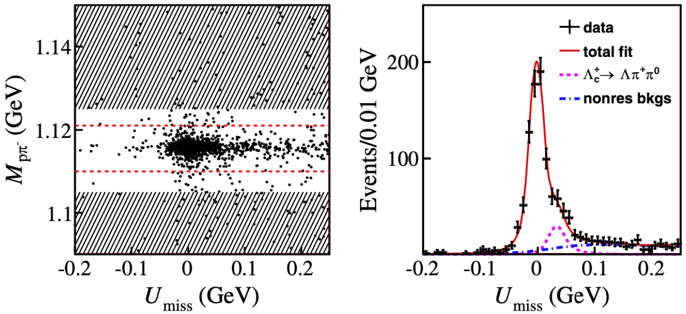






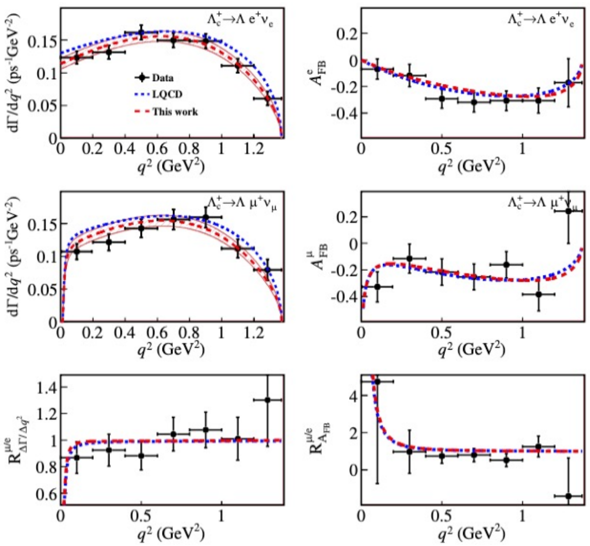
- BF is updated to be $\mathcal{B}(\Lambda_c^+ \to \Lambda e^+ \nu_e) = (3.56 \pm 0.11_{stat} \pm 0.07_{syst})\%$=>precision improved.
- Helicity amplitude deduced form factors can be extracted with 4D fitting to data.
- The differential decay rate is roughly consistent with LQCD calculation while discrepancies can be noticed on FFs show different kinematic behaviors.
- |Vcs| element from charmed baryons is measured to be $0.936 \pm 0.017_{\mathcal{B}} \pm 0.024_{\rm LQCD} \pm 0.007_{\tau_{\Lambda c}}$ which is consistent with the value obtained in charmed mesons decay.

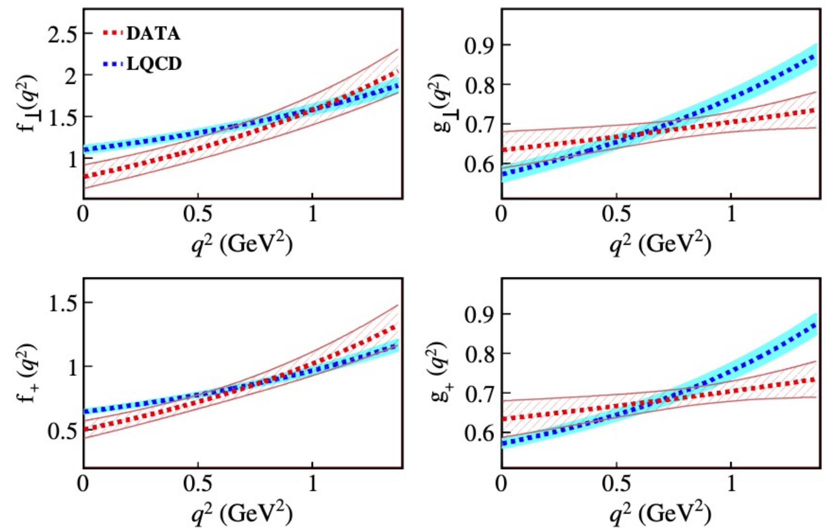
Form factors of $\Lambda_c^+ \rightarrow \Lambda\mu^+\nu_\mu$



PRD 108.L031105 (2023)

$$\frac{d^4\Gamma}{dq^2\, d\cos\theta'_\ell\, d\cos\theta_p\, d\chi} = \frac{G_F^2|V_{cs}|^2}{2(2\pi)^4}\cdot\frac{Pq^2(1-m_\ell^2/q^2)^2}{24M_{\Lambda_c}^2}\Big\{\frac{3}{8}(1-\cos\theta'_\ell)^2|H_{\frac{1}{2}1}|^2(1+\alpha_\Lambda\cos\theta_p) + \frac{3}{8}(1+\cos\theta'_\ell)^2|H_{-\frac{1}{2}-1}|^2(1-\alpha_\Lambda\cos\theta_p) + \frac{3}{4}\sin^2\theta'_\ell[|H_{\frac{1}{2}0}|^2(1+\alpha_\Lambda\cos\theta_p)+|H_{-\frac{1}{2}0}|^2(1-\alpha_\Lambda\cos\theta_p)] + \frac{3}{2\sqrt{2}}\alpha_\Lambda\cos\chi\sin\theta'_\ell\sin\theta_p \times[(1-\cos\theta'_\ell)H_{-\frac{1}{2}0}H_{\frac{1}{2}1}+(1+\cos\theta'_\ell)H_{\frac{1}{2}0}H_{-\frac{1}{2}-1}]+\mathcal{H}_{m_\ell^2}\Big\},$$

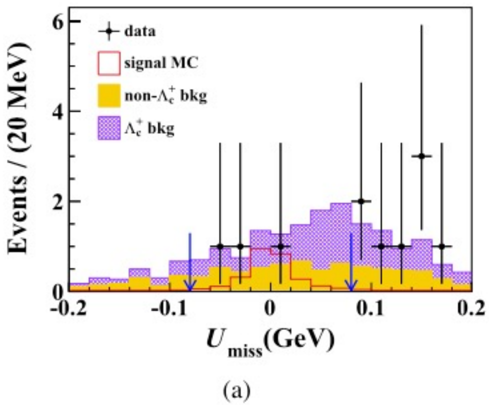


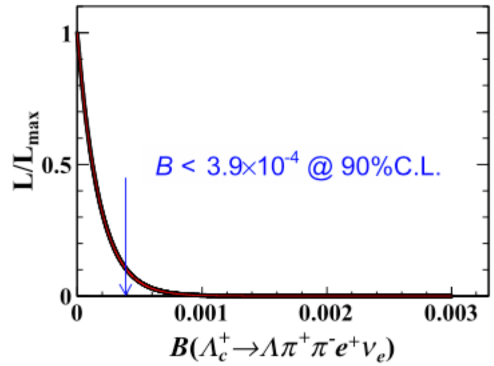


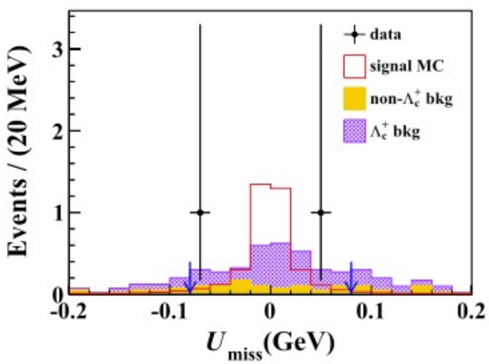
- BF is updated to be $\mathcal{B}(\Lambda_c^+ \rightarrow \Lambda\mu^+\nu_\mu) = (3.48 \pm 0.14_{stat} \pm 0.10_{syst})\%$=>3times more precise than prior results.
- Lepton flavor universality are reported $(0.98 \pm 0.05_{stat} \pm 0.03_{syst})$ =>compatible with Standard Model(0,97).
- Form-factors parameters for$\Lambda_c^+ \rightarrow \Lambda l^+\nu_l$ are determined to test and calibrate for LQCD.

$\Lambda_c^+ \to \Lambda\pi^+\pi^- e^+\nu_e$, $pK_s^0\pi^- e^+\nu_e$

PLB 843.137993 (2023)







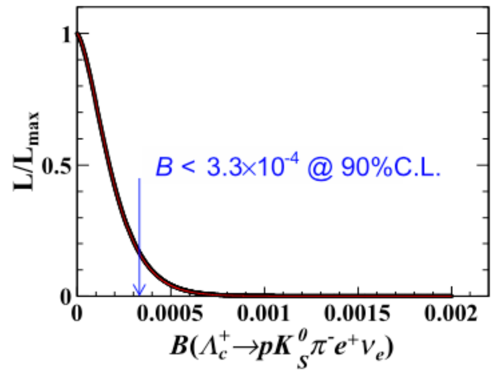


Table 1
The BFs for $\Lambda_c^+ \to \Lambda^* e^+\nu_e$ predicted by different theoretical models, in units of 10^{-4}.

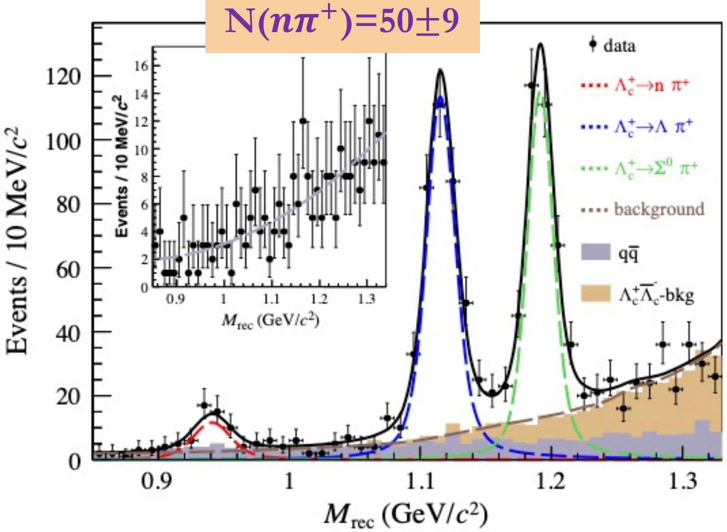
Λ^* state	CQM [8]	NRQM [9]	LFQM [10]	LQCD [11]
$\Lambda(1520)$	10.00	5.94	--	5.12 ± 0.82
$\Lambda(1600)$	4.00	1.26	(0.7 ± 0.2)	--
$\Lambda(1890)$	--	3.16×10^{-2}	--	--
$\Lambda(1820)$	--	1.32×10^{-2}	--	--

- 4.5fb^{-1} e^+e^- annihilation data are used to search $\Lambda_c^+ \to \Lambda\pi^+\pi^- e^+\nu_e$, $pK_s^0\pi^- e^+\nu_e$
- No significant signal is observed and hence the upper limits on BFs are set to be $\mathcal{B}(\Lambda_c^+ \to \Lambda\pi^+\pi^- e^+\nu_e) < 3.9\times10^{-4}$ and $\mathcal{B}(\Lambda_c^+ \to pK_s^0\pi^- e^+\nu_e) < 3.3\times10^{-4}$ at 90% CL.
- $\mathcal{B}(\Lambda_c^+ \to \Lambda(1520)e^+\nu_e) < 4.3\times10^{-3}$ and $\mathcal{B}(\Lambda_c^+ \to \Lambda(1600)e^+\nu_e) < 9.0\times10^{-3}$ at 90% CL assuming all $\Lambda\pi^+\pi^-$ combinations come from Λ^*.
- Limited sensitivity to identify different theoretical calculations.

First observation of $\Lambda_c^+ \to n\pi^+$

PRL 128.142001 (2022).

N($n\pi^+$)=50±9



- First singly Cabibbo-suppressed Λ_c^+ decay involved neutron was observed(7.3σ).
- Absolute BF is measured to be $\mathcal{B}(\Lambda_c^+ \to n\pi^+)= (6.6 \pm 1.2_{stat} \pm 0.4_{syst})\times10^{-4}$.
  =>Consistent with SU(3) flavor asymmetry prediction[PLB790,225(2019),]
  =>twice larger than the dynamical calculation based on pole model and CA[PRD97,074028(2018)]
- $\mathcal{B}(\Lambda_c^+ \to \Lambda\pi^+)= (1.31 \pm 0.08_{stat} \pm 0.05_{syst})\times10^{-2}$=>Consistent with previous BESIII results
- $\mathcal{B}(\Lambda_c^+ \to \Sigma^0\pi^+)= (1.22 \pm 0.08_{stat} \pm 0.07_{syst})\times10^{-2}$ =>Consistent with previous BESIII results
- $R = \frac{\mathcal{B}(\Lambda_c^+\to n\pi^+)}{\mathcal{B}(\Lambda_c^+\to p\pi^0)} > 7.2@90\%C.L.$ ($\mathcal{B}(\Lambda_c^+ \to p\pi^0)< 8.0\times10^{-5}$ @90%C.L.from Belle)
  =>Disagrees with SU(3) flavor asymmetry and dynamical calculation (2-4.7) while in consistent with SU(3) plus topological-diagram approach(9.6).

Decay asymmetry for pure W-exchange process $\Lambda_c^+ \to \Xi^0 K^+$

arXiv2309.02774(PRL accepted)

Theory or experiment	$\mathcal{B}(\Lambda_c^+ \to \Xi^0 K^+)$ $(\times 10^{-3})$	$\alpha_{\Xi^0 K^+}$	$\|A\|$ $(\times 10^{-2} G_F\ \mathrm{GeV}^2)$	$\|B\|$ $(\times 10^{-2} G_F\ \mathrm{GeV}^2)$	$\delta_p - \delta_s$ (rad)
Körner (1992), CCQM [7]	2.6	0	-	-	-
Xu (1992), Pole [8]	1.0	0	0	7.94	-
Źencaykowski (1994), Pole [9]	3.6	0	-	-	-
Ivanov (1998), CCQM [10]	3.1	0	-	-	-
Sharma (1999), CA [11]	1.3	0	-	-	-
Geng (2019), SU(3) [12]	5.7 ± 0.9	$0.94^{+0.06}_{-0.11}$	2.7 ± 0.6	16.1 ± 2.6	-
Zou (2020), CA [5]	7.1	0.90	4.48	12.10	-
Zhong (2022), SU(3)[a] [13]	$3.8^{+0.4}_{-0.5}$	$0.91^{+0.03}_{-0.04}$	3.2 ± 0.2	$8.7^{+0.6}_{-0.8}$	-
Zhong (2022), SU(3)[b] [13]	$5.0^{+0.6}_{-0.9}$	0.99 ± 0.01	$3.3^{+0.5}_{-0.7}$	$12.3^{+1.2}_{-1.8}$	-
BESIII (2018) [14]	$5.90 \pm 0.86 \pm 0.39$	-	-	-	-
PDG Fit (2022) [3]	5.5 ± 0.7	-	-	-	-

- $\Lambda_c^+ \to \Xi^0 K^+$ is pure W-exchange process which have significant contributions in charmed baryon decay.
- Nonfactorizable W-exchange diagram cannot be calculated using theoretical approaches.
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- Long-standing puzzle on how large the S-wave amplitude.
- Experimental measurement of decay asymmetry is crucial and urgent.

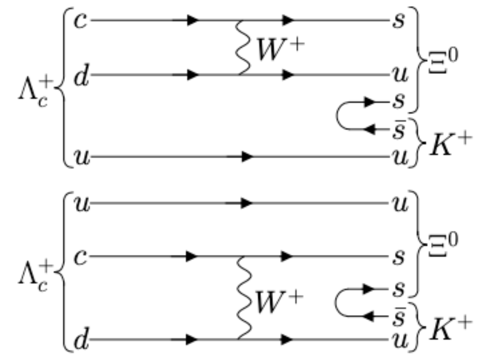


FIG. 1. Feynman diagrams for $\Lambda_c^+ \to \Xi^0 K^+$

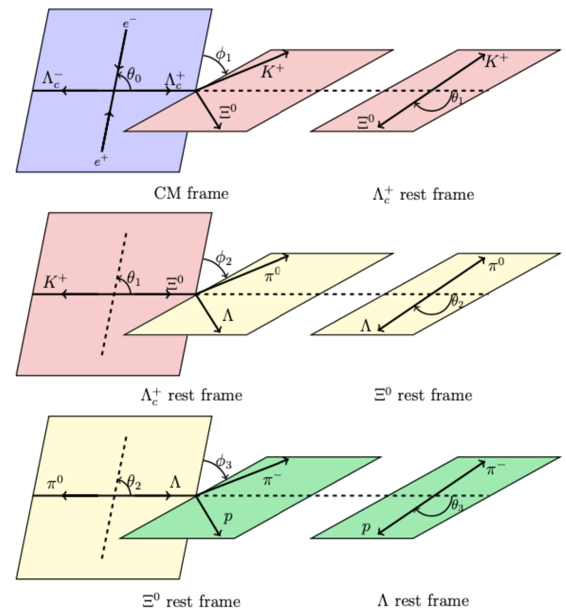
Decay asymmetry for pure W-exchange process $\Lambda_c^+ \to \Xi^0 K^+$

arXiv2309.02774(PRL accepted)

$$\alpha_{BP} = \frac{2\mathrm{Re}(s^*p)}{|s|^2+|p|^2}, \quad \beta_{BP} = \frac{2\mathrm{Im}(s^*p)}{|s|^2+|p|^2}, \quad \gamma_{BP} = \frac{|s|^2-|p|^2}{|s|^2+|p|^2},$$

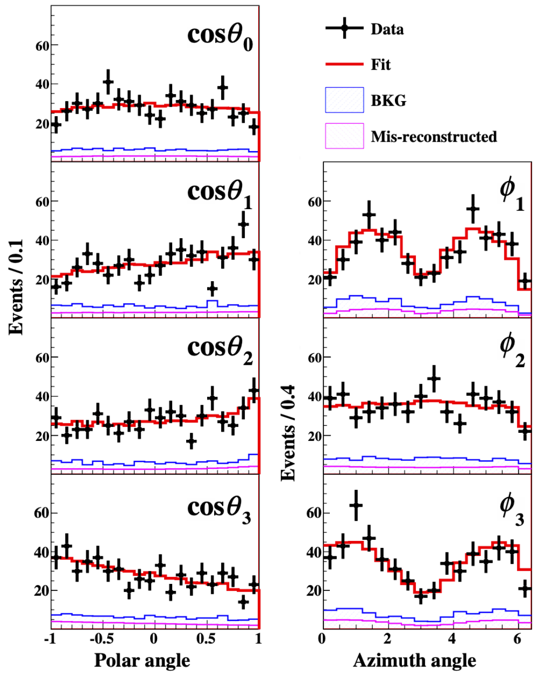
Level	Decay	Helicity angle	Helicity amplitude
0	$e^+e^- \to \Lambda_c^+(\lambda_1)\,\bar{\Lambda}_c^-(\lambda_2)$	(θ_0)	A_{λ_1,λ_2}
1	$\Lambda_c^+ \to \Xi^0(\lambda_3)\,K^+$	(θ_1,ϕ_1)	B_{λ_3}
2	$\Xi^0 \to \Lambda(\lambda_4)\,\pi^0$	(θ_2,ϕ_2)	C_{λ_4}
3	$\Lambda \to p(\lambda_5)\,\pi^-$	(θ_3,ϕ_3)	D_{λ_5}

$$\begin{aligned}
&\frac{d\Gamma}{d\cos\theta_0\; d\cos\theta_1\; d\cos\theta_2\; d\cos\theta_3\; d\phi_1\; d\phi_2\; d\phi_3} \\
&\propto 1+\alpha_0\cos^2\theta_0 \\
&+(1+\alpha_0\cos^2\theta_0)\;\alpha_{\Xi^0K^+}\alpha_{\Lambda\pi^0}\cos\theta_2 \\
&+(1+\alpha_0\cos^2\theta_0)\;\alpha_{\Xi^0K^+}\alpha_{p\pi^-}\cos\theta_2\cos\theta_3 \\
&+(1+\alpha_0\cos^2\theta_0)\;\alpha_{\Lambda\pi^0}\alpha_{p\pi^-}\cos\theta_3 \\
&-(1+\alpha_0\cos^2\theta_0)\;\alpha_{\Xi^0K^+}\sqrt{1-\alpha^2_{\Lambda\pi^0}}\;\alpha_{p\pi^-}\sin\theta_2\sin\theta_3\cos(\Delta_{\Lambda\pi^0}+\phi_3) \\
&+\sqrt{1-\alpha_0^2}\;\sin\Delta_0\sin\theta_0\cos\theta_0\alpha_{\Xi^0K^+}\sin\theta_1\sin\phi_1 \\
&+\sqrt{1-\alpha_0^2}\;\sin\Delta_0\sin\theta_0\cos\theta_0\alpha_{\Lambda\pi^0}\sin\theta_1\sin\phi_1\cos\theta_2 \\
&+\sqrt{1-\alpha_0^2}\;\sin\Delta_0\sin\theta_0\cos\theta_0\alpha_{\Xi^0K^+}\alpha_{\Lambda\pi^0}\alpha_{p\pi^-}\sin\theta_1\sin\phi_1\cos\theta_3 \\
&+\sqrt{1-\alpha_0^2}\;\sin\Delta_0\sin\theta_0\cos\theta_0\alpha_{p\pi^-}\sin\theta_1\sin\phi_1\cos\theta_2\cos\theta_3 \\
&-\sqrt{1-\alpha_0^2}\;\sin\Delta_0\sin\theta_0\cos\theta_0\sqrt{1-\alpha^2_{\Lambda\pi^0}}\;\alpha_{p\pi^-}\sin\theta_1\sin\phi_1\sin\theta_2\sin\theta_3\cos(\Delta_{\Lambda\pi^0}+\phi_3) \\
&+\sqrt{1-\alpha_0^2}\;\sin\Delta_0\sin\theta_0\cos\theta_0\sqrt{1-\alpha^2_{\Xi^0K^+}}\;\alpha_{\Lambda\pi^0}\cos\phi_1\sin\theta_2\sin(\Delta_{\Xi^0K^+}+\phi_2) \\
&+\sqrt{1-\alpha_0^2}\;\sin\Delta_0\sin\theta_0\cos\theta_0\sqrt{1-\alpha^2_{\Xi^0K^+}}\;\alpha_{\Lambda\pi^0}\cos\theta_1\sin\phi_1\sin\theta_2\cos(\Delta_{\Xi^0K^+}+\phi_2) \\
&+\sqrt{1-\alpha_0^2}\;\sin\Delta_0\sin\theta_0\cos\theta_0\sqrt{1-\alpha^2_{\Xi^0K^+}}\;\alpha_{p\pi^-}\cos\theta_1\sin\phi_1\sin\theta_2\cos(\Delta_{\Xi^0K^+}+\phi_2)\cos\theta_3 \\
&+\sqrt{1-\alpha_0^2}\;\sin\Delta_0\sin\theta_0\cos\theta_0\sqrt{1-\alpha^2_{\Xi^0K^+}}\;\alpha_{p\pi^-}\cos\phi_1\sin\theta_2\sin(\Delta_{\Xi^0K^+}+\phi_2)\cos\theta_3 \\
&-\sqrt{1-\alpha_0^2}\;\sin\Delta_0\sin\theta_0\cos\theta_0\sqrt{1-\alpha^2_{\Xi^0K^+}}\sqrt{1-\alpha^2_{\Lambda\pi^0}}\;\alpha_{p\pi^-}\cos\theta_1\sin\phi_1\sin(\Delta_{\Xi^0K^+}+\phi_2)\sin\theta_3\sin(\Delta_{\Lambda\pi^0}+\phi_3) \\
&+\sqrt{1-\alpha_0^2}\;\sin\Delta_0\sin\theta_0\cos\theta_0\sqrt{1-\alpha^2_{\Xi^0K^+}}\sqrt{1-\alpha^2_{\Lambda\pi^0}}\;\alpha_{p\pi^-}\cos\theta_1\sin\phi_1\cos\theta_2\cos(\Delta_{\Xi^0K^+}+\phi_2)\sin\theta_3\cos(\Delta_{\Lambda\pi^0}+\phi_3) \\
&+\sqrt{1-\alpha_0^2}\;\sin\Delta_0\sin\theta_0\cos\theta_0\sqrt{1-\alpha^2_{\Xi^0K^+}}\sqrt{1-\alpha^2_{\Lambda\pi^0}}\;\alpha_{p\pi^-}\cos\phi_1\cos(\Delta_{\Xi^0K^+}+\phi_2)\sin\theta_3\sin(\Delta_{\Lambda\pi^0}+\phi_3) \\
&+\sqrt{1-\alpha_0^2}\;\sin\Delta_0\sin\theta_0\cos\theta_0\sqrt{1-\alpha^2_{\Xi^0K^+}}\sqrt{1-\alpha^2_{\Lambda\pi^0}}\;\alpha_{p\pi^-}\cos\phi_1\cos\theta_2\sin(\Delta_{\Xi^0K^+}+\phi_2)\sin\theta_3\cos(\Delta_{\Lambda\pi^0}+\phi_3)
\end{aligned}$$



- The joint angular distribution for $\Lambda_c^+ \to \Xi^0 K^+$ is derived based on helicity amplitude.

Decay asymmetry for pure W-exchange process $\Lambda_c^+ \to \Xi^0 K^+$



arXiv2309.02774(PRL accepted)

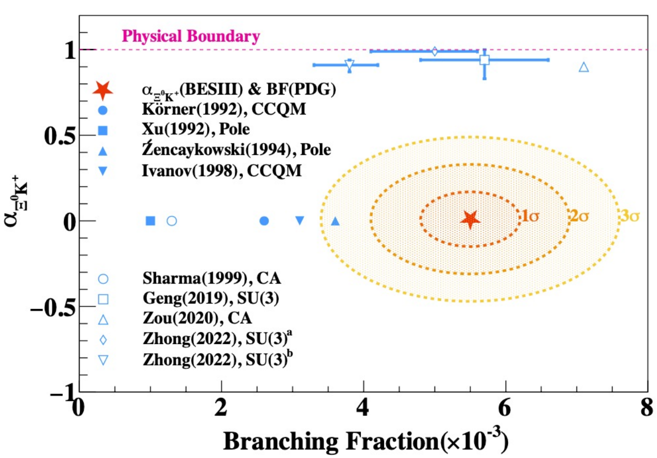
- From the fit, we obtain $\alpha_{\Xi^0 K^+} = 0.01 \pm 0.16_{stat} \pm 0.03_{syst}$ and $\beta_{\Xi^0 K^+} = -0.64 \pm 0.69_{stat} \pm 0.13_{syst}$ and $\gamma_{\Xi^0 K^+} = -0.77 \pm 0.58_{stat} \pm 0.11_{syst}$

- $\alpha_{\Xi^0 K^+}$ is in good agreement with zero=>strong identification for theoretical predictions.

$$\Gamma = \frac{\mathcal{B}(\Lambda_c^+ \to \Xi^0 K^+)}{\tau_{\Lambda_c^+}} = \frac{|\vec{p}_c|}{8\pi}\left[\frac{(m_{\Lambda_c^+} + m_{\Xi^0})^2 - m_{K^+}^2}{m_{\Lambda_c^+}^2}|A|^2 + \frac{(m_{\Lambda_c^+} - m_{\Xi^0})^2 - m_{K^+}^2}{m_{\Lambda_c^+}^2}|B|^2\right]$$

$$\alpha_{\Xi^0 K^+} = \frac{2\kappa|A||B|\cos(\delta_p - \delta_s)}{|A|^2 + \kappa^2|B|^2},$$

$$\Delta_{\Xi^0 K^+} = \arctan\frac{2\kappa|A||B|\sin(\delta_p - \delta_s)}{|A|^2 - \kappa^2|B|^2},$$

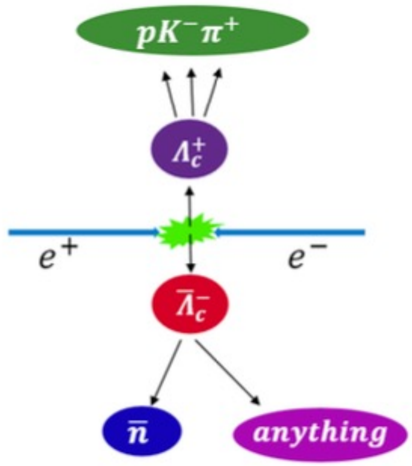


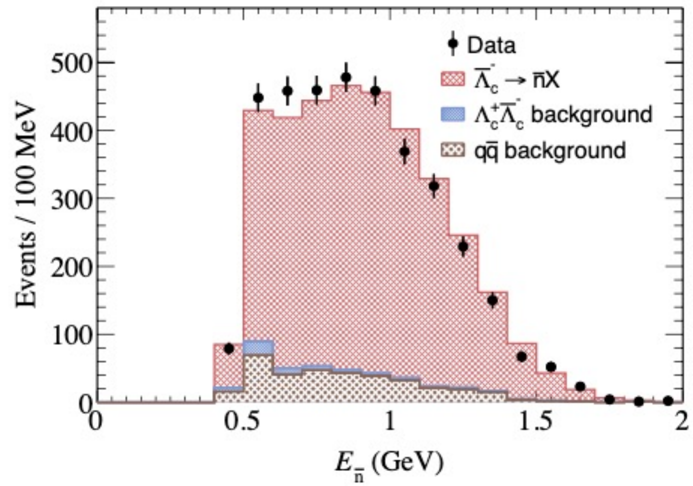
- Especially, $\cos(\delta_p - \delta_s)$ is measured to close to zero.=>not considered in previous literature.

- Fills the long-standing puzzle on how to model $\alpha_{\Xi^0 K^+}$ and $\mathcal{B}(\Lambda_c^+ \to \Xi^0 K^+)$ simultaneously.

BF measurement of $\bar{\Lambda}_c^- \to \bar{n}X$

PRD 108.L031101 (2023).

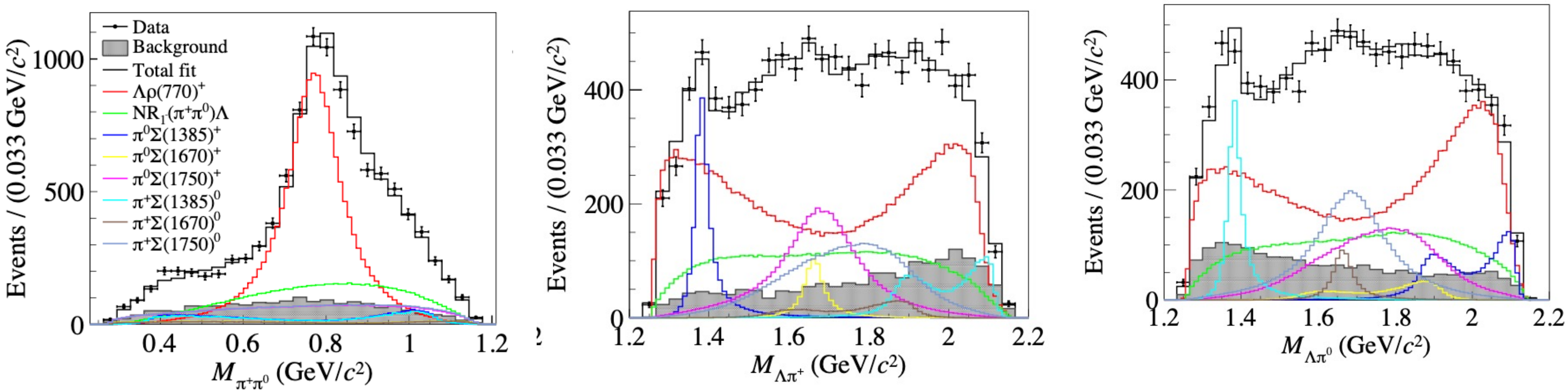




- The deposited energy in EMC is used to identify $\bar{n}$.
- Data-driven technique to model $\bar{n}$ behavior in the detector.
- Absolute BFs are measured to be $\mathcal{B}(\bar{\Lambda}_c^- \to \bar{n}X) = (33.5 \pm 0.7_{stat} \pm 1.2_{syst})\%$, precision up to 4%.
- All known exclusive process with neutron in final state is about 25%=>more space to be explored.
- Asymmetry between $\mathcal{B}(\Lambda_c^+ \to nX)$ and $\mathcal{B}(\Lambda_c^+ \to pX)$ is observed.

PWA for $\Lambda_c^+ \to \Lambda\pi^+\pi^0$

JHEP 12.033 (2022).



Process	Magnitude	Phase ϕ (rad)	FF (%)	Significance
$\Lambda\rho(770)^+$	1.0 (fixed)	0.0 (fixed)	57.2 ± 4.2	$36.9\,\sigma$
$\Sigma(1385)^+\pi^0$	0.43 ± 0.06	-0.23 ± 0.18	7.18 ± 0.60	$14.8\,\sigma$
$\Sigma(1385)^0\pi^+$	0.37 ± 0.07	2.84 ± 0.23	7.92 ± 0.72	$16.0\,\sigma$
$\Sigma(1670)^+\pi^0$	0.31 ± 0.08	-0.77 ± 0.23	2.90 ± 0.63	$5.1\,\sigma$
$\Sigma(1670)^0\pi^+$	0.41 ± 0.07	2.77 ± 0.20	2.65 ± 0.58	$5.2\,\sigma$
$\Sigma(1750)^+\pi^0$	1.75 ± 0.21	-1.73 ± 0.11	16.6 ± 2.2	$10.1\,\sigma$
$\Sigma(1750)^0\pi^+$	1.83 ± 0.21	1.34 ± 0.11	17.5 ± 2.3	$10.2\,\sigma$
$\Lambda + NR_{1^-}$	4.05 ± 0.47	2.16 ± 0.13	29.7 ± 4.5	$10.5\,\sigma$

- About 10K events survived which purity is larger than 80%.
- PWA based on helicity amplitude is performed.
- Interference mostly exist between $\Lambda\rho(770)$ and $\Sigma(1385)^{0/+}\pi^{+/0}$.

PWA for $\Lambda_c^+ \to \Lambda\pi^+\pi^0$

JHEP 12.033 (2022).

Amplitude	Magnitude	Phase ϕ (rad)	Amplitude	Magnitude	Phase ϕ (rad)
$\frac{1}{2}^+(\Lambda_c^+) \to \frac{3}{2}^+(\Sigma(1385)^+) + 0^-(\pi^0)$			$\frac{1}{2}^+(\Lambda_c^+) \to \frac{3}{2}^+(\Sigma(1385)^0) + 0^-(\pi^+)$		
$g_{1,\frac{3}{2}}^{\Sigma(1385)^+}$	1.0 (fixed)	0.0 (fixed)	$g_{1,\frac{3}{2}}^{\Sigma(1385)^0}$	1.0 (fixed)	0.0 (fixed)
$g_{2,\frac{3}{2}}^{\Sigma(1385)^+}$	1.29 ± 0.25	2.82 ± 0.18	$g_{2,\frac{3}{2}}^{\Sigma(1385)^0}$	1.70 ± 0.38	2.70 ± 0.22
$\frac{1}{2}^+(\Lambda_c^+) \to \frac{3}{2}^-(\Sigma(1670)^+) + 0^-(\pi^0)$			$\frac{1}{2}^+(\Lambda_c^+) \to \frac{3}{2}^-(\Sigma(1670)^0) + 0^-(\pi^+)$		
Amplitude	Magnitude	Phase ϕ (rad)	Amplitude	Magnitude	Phase ϕ (rad)
$g_{1,\frac{3}{2}}^{\Sigma(1670)^+}$	1.0 (fixed)	0.0 (fixed)	$g_{1,\frac{3}{2}}^{\Sigma(1670)^0}$	1.0 (fixed)	0.0 (fixed)
$g_{2,\frac{3}{2}}^{\Sigma(1670)^+}$	1.39 ± 0.42	0.85 ± 0.26	$g_{2,\frac{3}{2}}^{\Sigma(1670)^0}$	0.74 ± 0.18	0.29 ± 0.24
$\frac{1}{2}^+(\Lambda_c^+) \to \frac{1}{2}^-(\Sigma(1750)^+) + 0^-(\pi^0)$			$\frac{1}{2}^+(\Lambda_c^+) \to \frac{1}{2}^-(\Sigma(1750)^0) + 0^-(\pi^+)$		
Amplitude	Magnitude	Phase ϕ (rad)	Amplitude	Magnitude	Phase ϕ (rad)
$g_{0,\frac{1}{2}}^{\Sigma(1750)^+}$	1.0 (fixed)	0.0 (fixed)	$g_{0,\frac{1}{2}}^{\Sigma(1750)^0}$	1.0 (fixed)	0.0 (fixed)
$g_{1,\frac{1}{2}}^{\Sigma(1750)^+}$	0.45 ± 0.10	-2.28 ± 0.22	$g_{1,\frac{1}{2}}^{\Sigma(1750)^0}$	0.38 ± 0.10	-2.03 ± 0.20
$\frac{1}{2}^+(\Lambda_c^+) \to \frac{1}{2}^+(\Lambda) + 1^-(\rho(770)^+)$			$\frac{1}{2}^+(\Lambda_c^+) \to \frac{1}{2}^+(\Lambda) + 1^-(NR_{1^-})$		
Amplitude	Magnitude	Phase ϕ (rad)	Amplitude	Magnitude	Phase ϕ (rad)
$g_{0,\frac{1}{2}}^{\rho}$	1.0 (fixed)	0.0 (fixed)	$g_{0,\frac{1}{2}}^{NR}$	1.0 (fixed)	0.0 (fixed)
$g_{1,\frac{1}{2}}^{\rho}$	0.48 ± 0.12	-1.69 ± 0.12	$g_{1,\frac{1}{2}}^{NR}$	0.94 ± 0.12	-0.49 ± 0.16
$g_{1,\frac{3}{2}}^{\rho}$	0.90 ± 0.10	0.48 ± 0.13	$g_{1,\frac{3}{2}}^{NR}$	0.21 ± 0.09	-2.84 ± 0.53
$g_{2,\frac{3}{2}}^{\rho}$	0.55 ± 0.08	-0.04 ± 0.18	$g_{2,\frac{3}{2}}^{NR}$	0.33 ± 0.14	-1.92 ± 0.30
$\frac{1}{2}^+(\Lambda) \to \frac{1}{2}^+(p) + 0^-(\pi^-)$					
Amplitude	Magnitude	Phase ϕ (rad)			
$g_{0,\frac{1}{2}}^{\Lambda}$	1.0 (fixed)	0.0 (fixed)			
$g_{1,\frac{1}{2}}^{\Lambda}$	0.435376 (fixed)	0.0 (fixed)			

$$\alpha_{\Lambda\rho(770)^+} = \frac{|H^{\rho}_{\frac{1}{2},1}|^2 - |H^{\rho}_{-\frac{1}{2},-1}|^2 + |H^{\rho}_{\frac{1}{2},0}|^2 - |H^{\rho}_{-\frac{1}{2},0}|^2}{|H^{\rho}_{\frac{1}{2},1}|^2 + |H^{\rho}_{-\frac{1}{2},-1}|^2 + |H^{\rho}_{\frac{1}{2},0}|^2 + |H^{\rho}_{-\frac{1}{2},0}|^2}$$

$$= \frac{\sqrt{\frac{1}{9}} \cdot 2 \cdot \Re\left(g^{\rho}_{0,\frac{1}{2}} \cdot \bar{g}^{\rho}_{1,\frac{1}{2}} - g^{\rho}_{1,\frac{3}{2}} \cdot \bar{g}^{\rho}_{2,\frac{3}{2}}\right) - \sqrt{\frac{8}{9}} \cdot 2 \cdot \Re\left(g^{\rho}_{0,\frac{1}{2}} \cdot \bar{g}^{\rho}_{1,\frac{3}{2}} + g^{\rho}_{1,\frac{1}{2}} \cdot \bar{g}^{\rho}_{2,\frac{3}{2}}\right)}{|g^{\rho}_{0,\frac{1}{2}}|^2 + |g^{\rho}_{1,\frac{1}{2}}|^2 + |g^{\rho}_{1,\frac{3}{2}}|^2 + |g^{\rho}_{2,\frac{3}{2}}|^2}. \quad (4.28)$$

$$\alpha_{\Sigma(1385)\pi} = \frac{|H^{\Sigma(1385)}_{0,\frac{1}{2}}|^2 - |H^{\Sigma(1385)}_{0,-\frac{1}{2}}|^2}{|H^{\Sigma(1385)}_{0,\frac{1}{2}}|^2 + |H^{\Sigma(1385)}_{0,-\frac{1}{2}}|^2} = \frac{2\Re\left(g^{\Sigma(1385)}_{1,\frac{3}{2}} \cdot \bar{g}^{\Sigma(1385)}_{2,\frac{3}{2}}\right)}{|g^{\Sigma(1385)}_{1,\frac{3}{2}}|^2 + |g^{\Sigma(1385)}_{2,\frac{3}{2}}|^2}.$$

- Decay asymmetry parameters can be obtained by the fit results of the partial wave amplitudes.

PWA for $\Lambda_c^+ \to \Lambda\pi^+\pi^0$

JHEP 12.033 (2022).

$$\frac{\mathcal{B}(\Lambda_c^+ \to \Lambda\rho(770)^+)}{\mathcal{B}(\Lambda_c^+ \to \Lambda\pi^+\pi^0)} = (57.2 \pm 4.2 \pm 4.9)\%,$$

$$\frac{\mathcal{B}(\Lambda_c^+ \to \Sigma(1385)^+\pi^0)\cdot\mathcal{B}(\Sigma(1385)^+ \to \Lambda\pi^+)}{\mathcal{B}(\Lambda_c^+ \to \Lambda\pi^+\pi^0)} = (7.18 \pm 0.60 \pm 0.64)\%,$$

$$\frac{\mathcal{B}(\Lambda_c^+ \to \Sigma(1385)^0\pi^+)\cdot\mathcal{B}(\Sigma(1385)^0 \to \Lambda\pi^0)}{\mathcal{B}(\Lambda_c^+ \to \Lambda\pi^+\pi^0)} = (7.92 \pm 0.72 \pm 0.80)\%.$$

$$\mathcal{B}(\Lambda_c^+ \to \Lambda\rho(770)^+) = (4.06 \pm 0.30 \pm 0.35 \pm 0.23)\%,$$

$$\mathcal{B}(\Lambda_c^+ \to \Sigma(1385)^+\pi^0) = (5.86 \pm 0.49 \pm 0.52 \pm 0.35) \times 10^{-3},$$

$$\mathcal{B}(\Lambda_c^+ \to \Sigma(1385)^0\pi^+) = (6.47 \pm 0.59 \pm 0.66 \pm 0.38) \times 10^{-3},$$

$$\alpha_{\Lambda\rho(770)^+} = -0.763 \pm 0.053 \pm 0.039,$$

$$\alpha_{\Sigma(1385)^+\pi^0} = -0.917 \pm 0.069 \pm 0.046,$$

$$\alpha_{\Sigma(1385)^0\pi^+} = -0.789 \pm 0.098 \pm 0.056.$$

Table 9. The comparison among this work, various theoretical calculations and PDG results. Here, the uncertainties of this work are the combined uncertainties. "—" means unavailable.

	Theoretical calculation		This work	PDG
$10^2 \times \mathcal{B}(\Lambda_c^+ \to \Lambda\rho(770)^+)$	4.81 ± 0.58 [13]	4.0 [14, 15]	4.06 ± 0.52	< 6
$10^3 \times \mathcal{B}(\Lambda_c^+ \to \Sigma(1385)^+\pi^0)$	2.8 ± 0.4 [16]	2.2 ± 0.4 [17]	5.86 ± 0.80	—
$10^3 \times \mathcal{B}(\Lambda_c^+ \to \Sigma(1385)^0\pi^+)$	2.8 ± 0.4 [16]	2.2 ± 0.4 [17]	6.47 ± 0.96	—
$\alpha_{\Lambda\rho(770)^+}$	-0.27 ± 0.04 [13]	-0.32 [14, 15]	-0.763 ± 0.066	—
$\alpha_{\Sigma(1385)^+\pi^0}$	$-0.91^{+0.45}_{-0.10}$ [17]		-0.917 ± 0.083	—
$\alpha_{\Sigma(1385)^0\pi^+}$	$-0.91^{+0.45}_{-0.10}$ [17]		-0.79 ± 0.11	—

- NO theoretical models is able to explain both BFs and decay asymmetries simultaneously.
- Fruitful results are extracted which provide crucial input to extend the understanding of dynamics of charmed baryon hadronic decays.

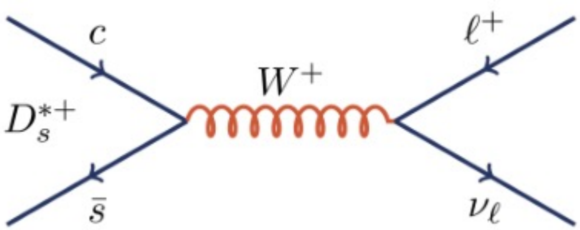
Recent studies on the charmed mesons at BESIII

- $D^{\pm}, D^0, D_s^+$ purely leptonic decays
  - $D_s^{*+} \to e^+\nu_e$: PRL 131, 141802 (2023). ✓
  - $D_s^+ \to \mu^+\nu_\mu$: PRD 108, 112001 (2023).
  - $D_s^+ \to \tau^+\nu_\tau, \tau^+ \to \mu^+\nu_\mu\bar{\nu}_\tau$: JHEP 09 (2023) 124.
  - $D_s^+ \to \tau^+\nu_\tau, \tau^+ \to \pi^+\bar{\nu}_\tau$: PRD 108, 092014 (2023).
- $D^{\pm}, D^0, D_s^+$ semi-leptonic decays
  - $D_s^+ \to K_1(1270)/b_1(1235)e^+\nu_e$: PRD 108, 112002 (2023). ✓
  - $D_s^+ \to \eta(\eta')e^+\nu_e$: PRD 108, 092003 (2023).
- $D^{\pm}, D^0, D_s^+$ hadronic decays
  - $D^+ \to K_S^0\pi^+\pi^0\pi^0$: JHEP 09 (2023) 077. ✓
  - $D_s^+ \to \omega\pi^+\eta$: PRD 107, 052010 (2023).
- $D^{\pm}, D^0, D_s^+$ inclusive decays
  - $D^{+/0} \to K_S^0 X$: PRD 107, 112005 (2023). ✓
  - $D^{+/0} \to \pi^+\pi^+\pi^- X$: PRD 107, 032002 (2023).
  - $D_s^+ \to \pi^+\pi^+\pi^- X$: PRD 108, 032001 (2023).
- Strong phase in $D^{\pm}, D^0, D_s^+$ decays
  - $D^0 \to K_S^0\pi^+\pi^-\pi^0$: PRD 108, 032003 (2023). ✓
  - $D^0 \to K^+K^-\pi^+\pi^-$: PRD 107, 032009 (2023).
- Others
  - Determination of spin and parity of D_s^* : PLB 846, 138245 (2023). ✓
  - $D_s^* \to \gamma D_s$: PRD 107, 032011 (2023).

Purely leptonic decays of charmed meson

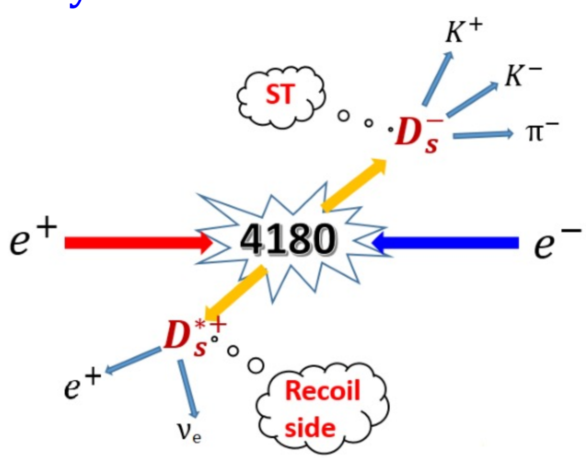
- First experimental study of the purely leptonic decay $D_s^{*+} \to e^+\nu_e$ [PRL 131, 141802 (2023)]

- Theoretical predicted to be $(3.4 \pm 1.4)\times 10^{-5}$ in Full Lattice QCD (PRL 112, 212002).
- Helpful to determine the decay constant $f_{D_s^{*+}}$, important to calibrate the LQCD calculation.
- Test lepton flavor university.

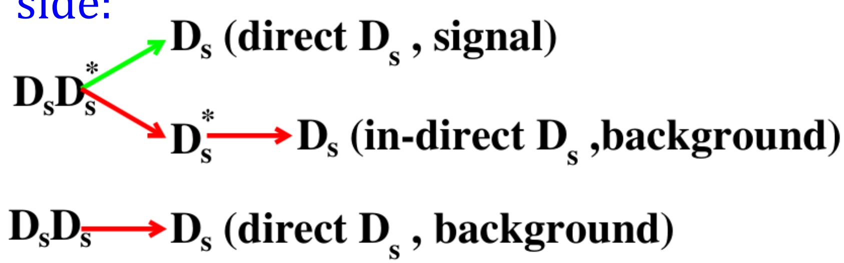


$$\Gamma_{(D_s^{*+}\to\ell^+\nu_\ell)} = \frac{G_F^2}{12\pi}|V_{cs}|^2 f_{D_s^{*+}}^2 M_{D_s^{*+}}^3 \left(1-\frac{m_{\ell^+}^2}{M_{D_s^{*+}}^2}\right)^2\left(1+\frac{m_{\ell^+}^2}{2M_{D_s^{*+}}^2}\right)$$

- Analysis method:



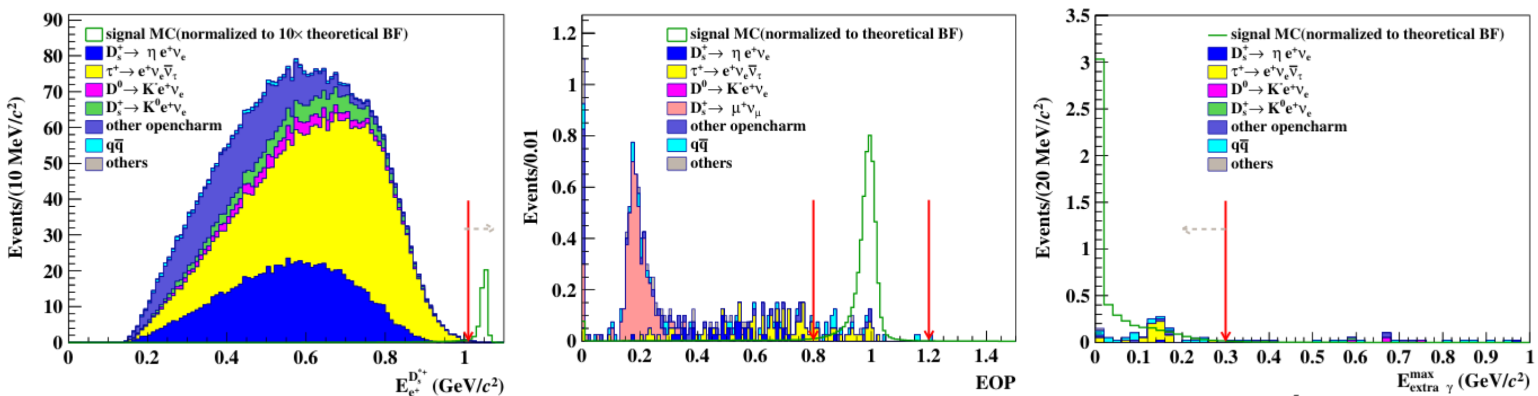
- For ST side:



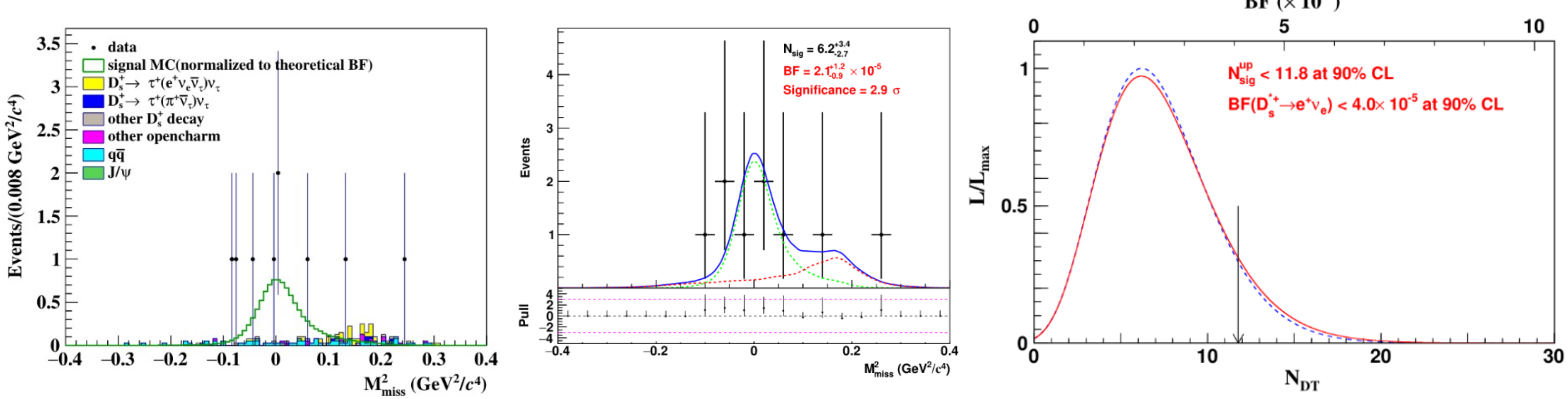
$$M_{\rm rec} = \sqrt{\left(E_{\rm cm} - \sqrt{(|\overrightarrow{P}_{D_s^-}|^2 + m_{D_s^-}^2)}\right)^2 - (-p_{D_s^-})^2}$$

Purely leptonic decays of charmed meson

- First experimental study of the purely leptonic decay $D_s^{*+} \to e^+\nu_e$ [PRL 131, 141802 (2023)]
- For signal side: $$M^2_{\rm miss} = (E_{\rm cm} - E_{\rm tag} - E_{D_s^{*+}})^2 - (-\vec{p}_{\rm tag} - \vec{p}_{D_s^{*+}})^2$$
- Selections:

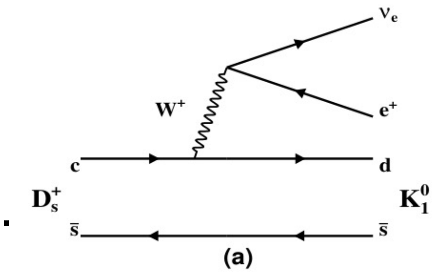


- Fits & UL:

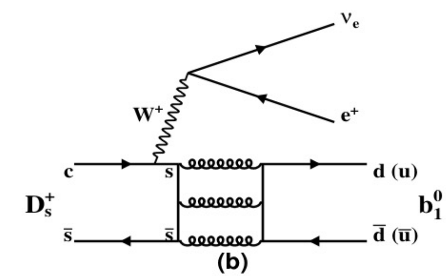


Semi-leptonic decays of charmed meson

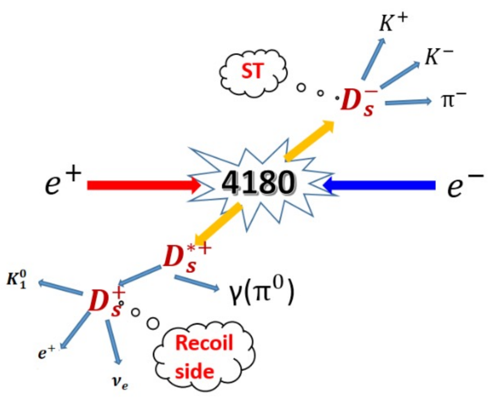
- Search for the semileptonic decays $D_s^+ \to K_1(1270)^0 e^+ \nu_e$ and $D_s^+ \to b_1(1235)^0 e^+ \nu_e$. [PRD 108, 112002 (2023)]

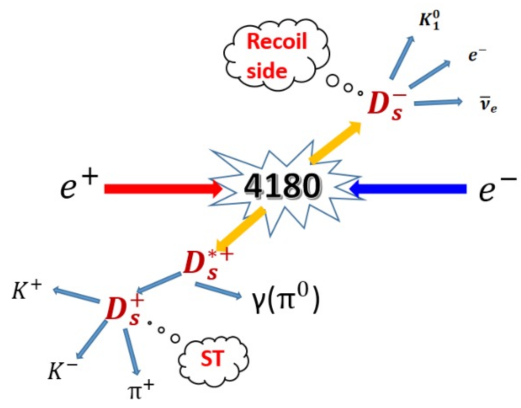


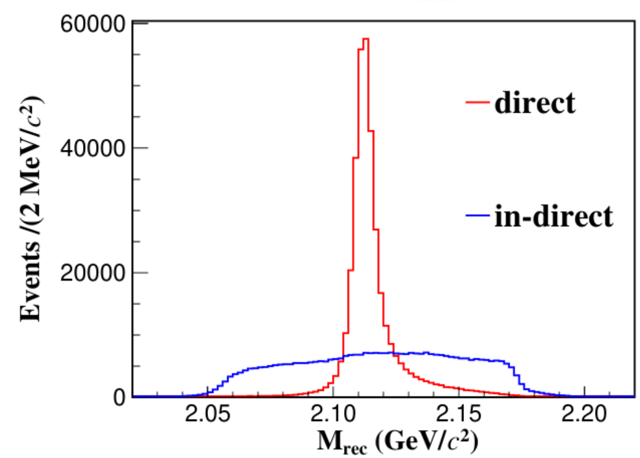
- Theoretical predicted to be 10^{-4} level. (EPJC 77, 587(2017)).
- First measurement of D_s decays to axial-vector mesons.
- Provide important input for study of photon helicity in $b \to s\gamma$.



- Analysis method:





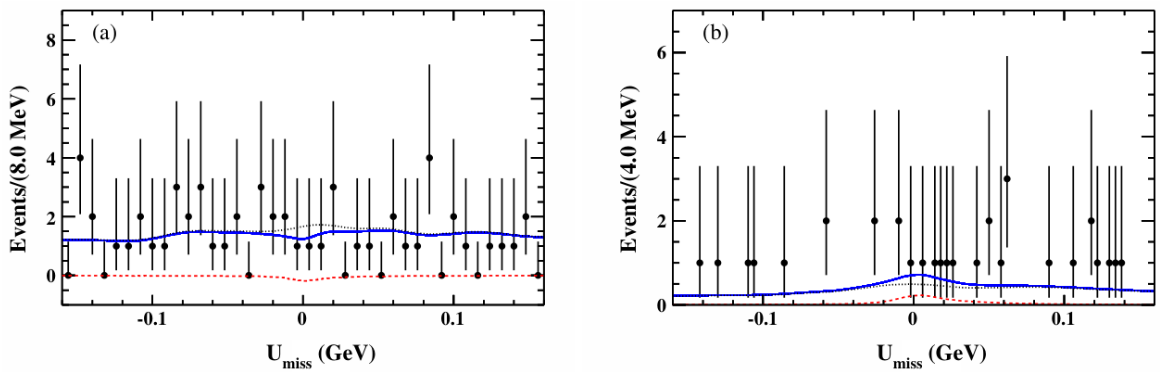


- For ST side:

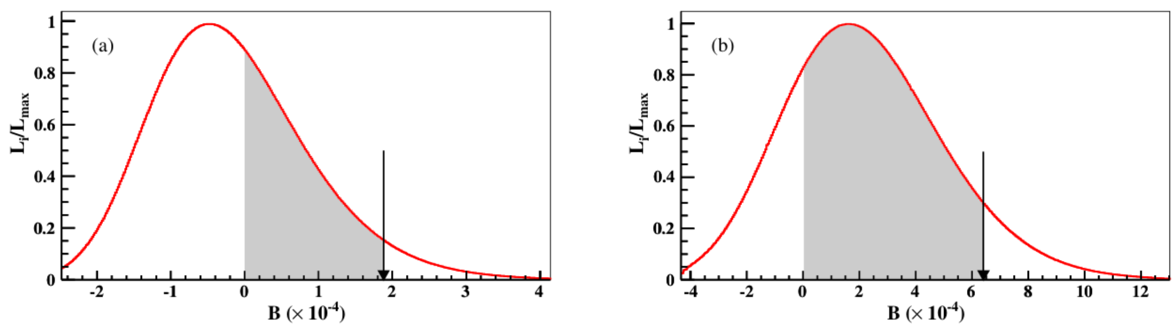
$$M_{\rm rec} = \sqrt{\left(E_{\rm cm} - \sqrt{(|\vec{P}_{D_s^-}|^2 + m^2_{D_s^-})}\right)^2 - (-p_{D_s^-})^2}$$

Semi-leptonic decays of charmed meson

- Search for the semileptonic decays $D_s^+ \to K_1(1270)^0 e^+ \nu_e$ and $D_s^+ \to b_1(1235)^0 e^+ \nu_e$. [PRD 108, 112002 (2023)]
- For signal side: $U_{\rm miss} = (E_{\rm cm} - E_{\rm tag} - E_{\gamma\pi^0} - E_{D_s^+}) - (-\vec{p}_{\rm tag} - \vec{p}_{\gamma\pi^0} - \vec{p}_{D_s^+})$
- Fits & UL:



$\mathcal{B}(D_s^+ \to K_1^0 e^+ \nu_e) \cdot \mathcal{B}(K_1^0 \to K^+ \pi^- \pi^0) < 1.9 \times 10^4$ $\mathcal{B}(D_s^+ \to b_1^0 e^+ \nu_e) \cdot \mathcal{B}(b_1^0 \to \omega \pi^0) < 6.4 \times 10^4$

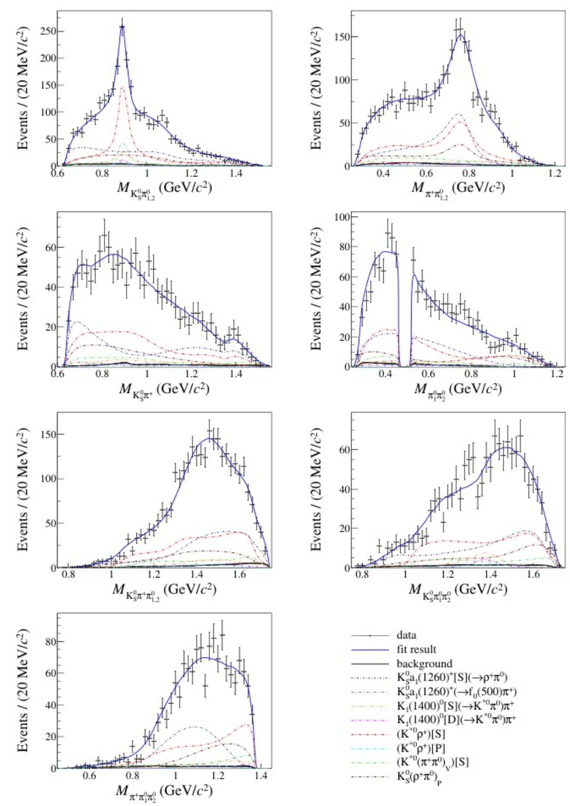


- First search for $D_s^+ \to K_1^0(1270) e^+ \nu_e$ and $D_s^+ \to b_1(1235)^0 e^+ \nu_e$, upper limit is set.

Hadronic decays of charmed meson

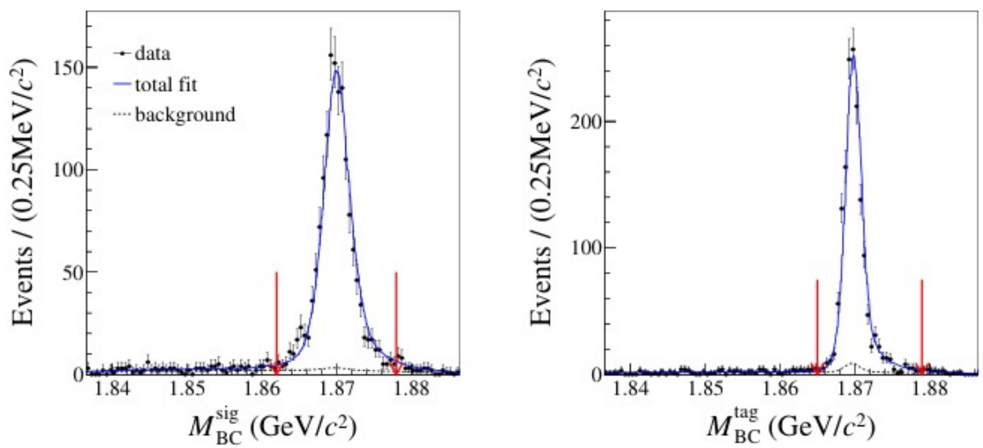
- Amplitude analysis and BF measurement of $D^+ \to K_S^0\pi^+\pi^0\pi^0$ [PLB 838, 137698 (2023)]

- First amplitude analysis for $D^+ \to K_S^0\pi^+\pi^0\pi^0$.
- Dominated by $D \to AP$, $D \to VV$ decays, the former can help to study substructures, the latter is useful in polarization measurement.
- Cabibbo-favored decay, with 2.9% BF, can be used as a "tag" mode.



- Double tag: $D^+ \to K_S^0\pi^+\pi^0\pi^0$ vs $D^- \to K^+\pi^-\pi^-$

- 2D fit:

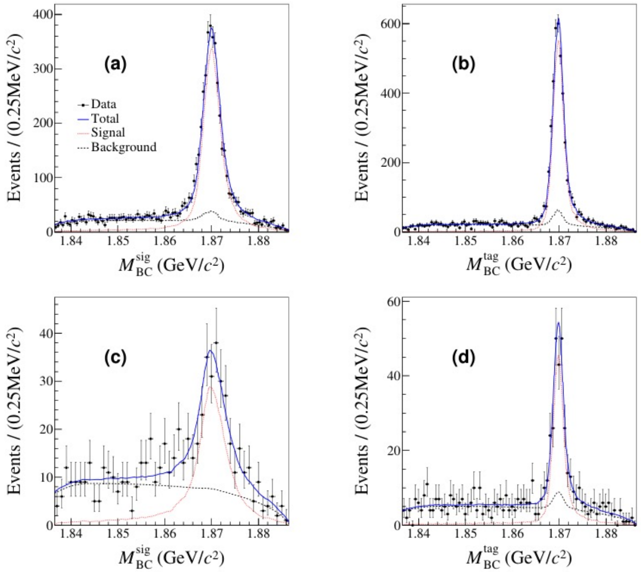


Hadronic decays of charmed meson

- Amplitude analysis and BF measurement of $D^+ \to K_S^0\pi^+\pi^0\pi^0$ [PLB 838, 137698 (2023)]

- Amplitude analysis results:

Amplitude	Phase ϕ_n (rad)	FF (%)	Significance (σ)
$D^+ \to K_S^0 a_1(1260)^+[S](\to \rho^+\pi^0)$	0.0 (fixed)	$30.0 \pm 3.6 \pm 4.2$	>10
$D^+ \to K_S^0 a_1(1260)^+(\to f_0(500)\pi^+)$	$4.78 \pm 0.22 \pm 0.20$	$3.5 \pm 1.1 \pm 1.9$	6.9
$D^+ \to \bar{K}_1(1400)^0[S](\to \bar{K}^{*0}\pi^0)\pi^+$	$-3.01 \pm 0.12 \pm 0.16$	$6.0 \pm 1.2 \pm 0.3$	9.6
$D^+ \to \bar{K}_1(1400)^0[D](\to \bar{K}^{*0}\pi^0)\pi^+$	$4.29 \pm 0.16 \pm 0.20$	$2.4 \pm 0.6 \pm 0.2$	6.7
$D^+ \to \bar{K}_1(1400)^0(\to \bar{K}^{*0}\pi^0)\pi^+$	—	$8.0 \pm 1.2 \pm 0.4$	—
$D^+[S] \to \bar{K}^{*0}\rho^+$	$-3.33 \pm 0.10 \pm 0.17$	$31.8 \pm 2.7 \pm 1.3$	>10
$D^+[P] \to \bar{K}^{*0}\rho^+$	$-1.68 \pm 0.17 \pm 0.16$	$1.7 \pm 0.6 \pm 0.1$	5.0
$D^+ \to \bar{K}^{*0}\rho^+$	—	$33.6 \pm 2.7 \pm 1.4$	—
$D^+[S] \to \bar{K}^{*0}(\pi^+\pi^0)_V$	$-5.60 \pm 0.13 \pm 0.16$	$9.1 \pm 2.0 \pm 1.0$	9.4
$D^+ \to K_S^0(\rho^+\pi^0)_P$	$0.76 \pm 0.11 \pm 0.24$	$16.5 \pm 1.6 \pm 0.3$	>10



- BF results:

Intermediate process	BF ($\times 10^{-3}$)
$D^+ \to K_S^0 a_1(1260)^+[S](\to \rho^+\pi^0)$	$8.66 \pm 1.04 \pm 1.24$
$D^+ \to K_S^0 a_1(1260)^+(\to f_0(500)\pi^+)$	$1.00 \pm 0.33 \pm 0.55$
$D^+ \to \bar{K}_1(1400)^0[S](\to \bar{K}^{*0}\pi^0)\pi^+$	$1.73 \pm 0.34 \pm 0.09$
$D^+ \to \bar{K}_1(1400)^0[D](\to \bar{K}^{*0}\pi^0)\pi^+$	$0.68 \pm 0.16 \pm 0.07$
$D^+ \to \bar{K}_1(1400)^0(\to \bar{K}^{*0}\pi^0)\pi^+$	$2.32 \pm 0.36 \pm 0.13$
$D^+[S] \to \bar{K}^{*0}\rho^+$	$9.20 \pm 0.80 \pm 0.45$
$D^+[P] \to \bar{K}^{*0}\rho^+$	$0.49 \pm 0.17 \pm 0.03$
$D^+ \to \bar{K}^{*0}\rho^+$	$9.70 \pm 0.81 \pm 0.47$
$D^+[S] \to \bar{K}^{*0}(\pi^+\pi^0)_V$	$2.63 \pm 0.57 \pm 0.30$
$D^+ \to K_S^0(\rho^+\pi^0)_P$	$4.75 \pm 0.46 \pm 0.14$

- BF measurement:

$$\mathcal{B}_{\rm sig} = \frac{N^{\rm DT}_{\rm total}}{\mathcal{B}_{\rm sub}\sum_\alpha N^{\rm ST}_\alpha \epsilon^{\rm DT}_{\alpha,{\rm sig}}/\epsilon^{\rm ST}_\alpha} \qquad N^{\rm DT}_{\rm total} = N^{\rm DT}_{K_S^0,{\rm sig}} - \frac{1}{2}N^{\rm DT}_{K_S^0,{\rm side}}$$

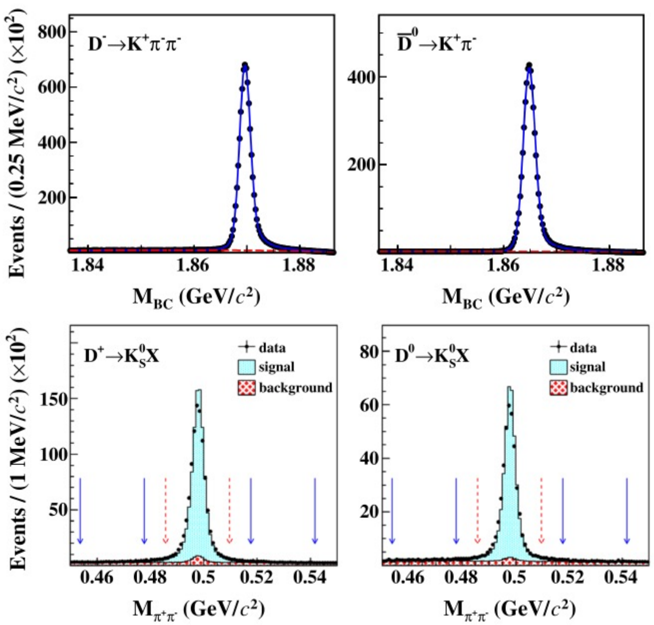
Inclusive decays of charmed meson

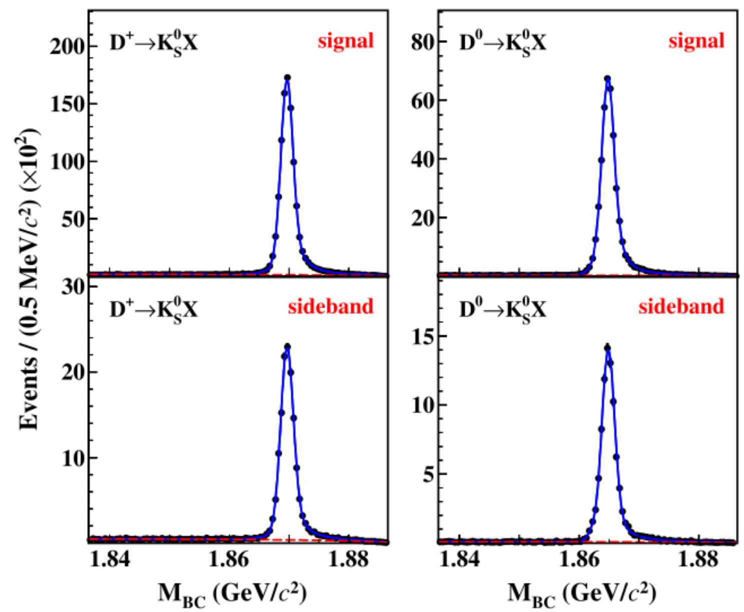
- Improved measurement of the BF of $D^{+/0} \to K_S^0 X$ [PRD 107, 112005 (2023)]

- Deeply explore the D decay mechanisms.
- Provides guide to search for more unobserved decay modes.
- Help tune D0 and D+ decay modes in inclusive MC samples.

- Double tag:

$$\mathcal{B}_{\rm sig} = \frac{N_{\rm DT}}{N_{\rm tag}\epsilon_{\rm sig}}$$



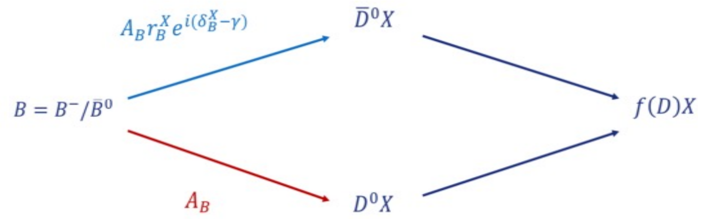


- BF results:

Decay mode	Mark-III (%) [1]	BES (%) [2]	PDG (%) [3]	This study (%)	$\mathcal{B}^{\rm sum}_{\rm exclusive}$ (%)
$D^+ \to K_S^0 X$	$30.60 \pm 3.25 \pm 2.15$	$30.25 \pm 2.75 \pm 1.65$	30.5 ± 2.5	$33.11 \pm 0.13 \pm 0.36$	31.68 ± 0.32
$D^0 \to K_S^0 X$	$22.75 \pm 2.50 \pm 1.60$	$23.80 \pm 2.40 \pm 1.50$	23.5 ± 2.0	$20.75 \pm 0.12 \pm 0.20$	18.16 ± 0.72

Strong phase in $D^{\pm}, D^0, D_s^+$ decays

- Determination of the CP-even fraction of $D^0 \to K_S^0\pi^+\pi^-\pi^0$
  [PRD 108, 032003 (2023)]



- The CKM unitarity angle $\gamma = \arg(-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*})$.
- The important source of CP violation for the quark sector.
- Search for indirect new physics.
- Test of CKM unitary.

$$Y^{\mp} = h^{\mp}\int_{\mathbf{x}\in\mathcal{D}} \mathcal{P}(B^{\mp}(\mathbf{x}))\,d\mathbf{x}$$
$$= h^{\mp}\left[1 + r_B^2 + \left(2F_+^f - 1\right)2r_B\cos(\delta_B \mp \gamma)\right]$$

- With F_+^f, the γ angle can be extracted.

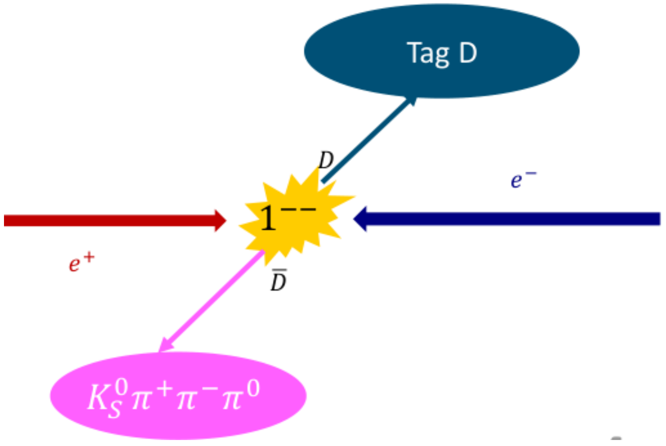
$\Rightarrow$ Important to determine F_+ for $D \to K_S^0\pi^+\pi^-\pi^0$.

- Double tag method:

- With CP tags
- With $\pi^+\pi^-\pi^0$ tag
- With $K_S^0\pi^+\pi^-\pi^0$ tag
- With $K_S^0\pi^+\pi^-$ tag

Type	Modes
CP-even	$K^+K^-, \pi^+\pi^-, K_S^0\pi^0\pi^0, K_L^0\omega, K_L^0\pi^0$
CP-odd	$K_S^0\pi^0, K_S^0\eta(\gamma\gamma), K_S^0\eta'(\eta\pi^+\pi^-), K_S^0\eta'(\gamma\pi^+\pi^-)$
Mixed CP	$\pi^+\pi^-\pi^0, \pi^+\pi^-\pi^+\pi^-, K_{S,L}^0\pi^+\pi^-, K_S^0\pi^+\pi^-\pi^0$

Mixed CP tag modes

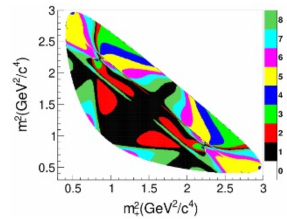


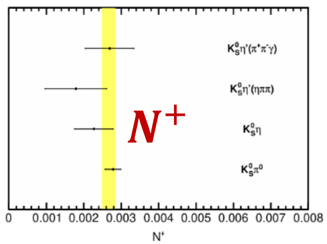
Strong phase in $D^{\pm}, D^0, D_s^+$ decays

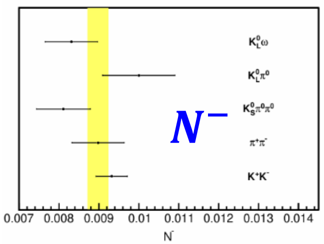
- Determination of the CP-even fraction of $D^0 \to K_S^0 \pi^+\pi^-\pi^0$ [PRD 108, 032003 (2023)]

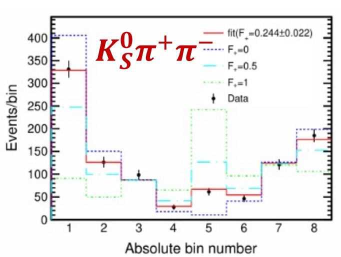
- Determination of F_+:

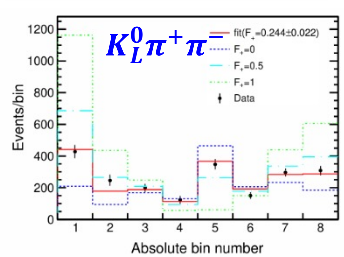
- With CP tags: $N^{\pm} = \mathcal{B}(S)\varepsilon(S)\left[1 - \eta_{CP}^{\mp}\left(2F_+^S - 1\right)\right]$ $\quad F_+ = \frac{N^+}{N^+ + N^-}$
- With $\pi^+\pi^-\pi^0$ tag: $\frac{N^{\pi^+\pi^-\pi^0}}{\langle N^+\rangle} = \frac{\left[1-\left(2F_+^S - 1\right)\left(2F_+^{\pi^+\pi^-\pi^0} - 1\right)\right]}{2F_+^S}$ $\quad F_+^S = \frac{\langle N^+\rangle F_+^{\pi^+\pi^-\pi^0}}{N^{\pi^+\pi^-\pi^0} - \langle N^+\rangle + 2\langle N^+\rangle F_+^{\pi^+\pi^-\pi^0}}$
- With $K_S^0\pi^+\pi^-\pi^0$ tag: $N^S = 2B_S\varepsilon(S)F_+^S\left(1 - F_+^S\right)$ $\quad F_+^S = \frac{N^S}{\langle N^-\rangle}$
- With $K_S^0\pi^+\pi^-$ and $K_L^0\pi^+\pi^-$ tags: Divided into 8 bins of δ_D.











- F_+ Results:

Method	F_+
CP tags	$0.229 \pm 0.013 \pm 0.0018$
$\pi^+\pi^-\pi^0$ tag	$0.227 \pm 0.014 \pm 0.0027$
$\pi^+\pi^-\pi^+\pi^-$ tag	$0.227 \pm 0.016 \pm 0.0034$
$K_S^0\pi^+\pi^-\pi^0$ self-tag	$0.244 \pm 0.019 \pm 0.0022$
$K_{S,L}^0\pi^+\pi^-$	$0.244 \pm 0.021 \pm 0.0062$
combined	$0.234 \pm 0.0096 \pm 0.0018$

Spin and parity of D_s^* meson

➢ Determination of spin and parity for D_s^* meson. [PLB 846, 138245 (2023)]

- There is no decisive experimental results of spin and parity have been reported for the ground 1S states $D_{(s)}^*$. In PDG, the status of J^P for D^{*0} and D^{*+} are assigned to be 1^- while they need to be confirmed experimentally.

CHARMED, STRANGE MESONS
($C = S = \pm1$)
$D_s^+ = c\bar{s}$, $D_s^- = \bar{c}s$, similarly for D_s^*'s

$D_s^{*\pm}$ $I(J^P) = 0(?^?)$

J^P is natural, width and decay modes consistent with 1^-

CHARMED MESONS
($C = \pm1$)
$D^+ = c\bar{d}$, $D^0 = c\bar{u}$, $\overline{D}^0 = \bar{c}u$, $D^- = \bar{c}d$, similarly for D^*'s

$D^*(2007)^0$ $I(J^P) = 1/2(1^-)$ I, J, P need confirmation.

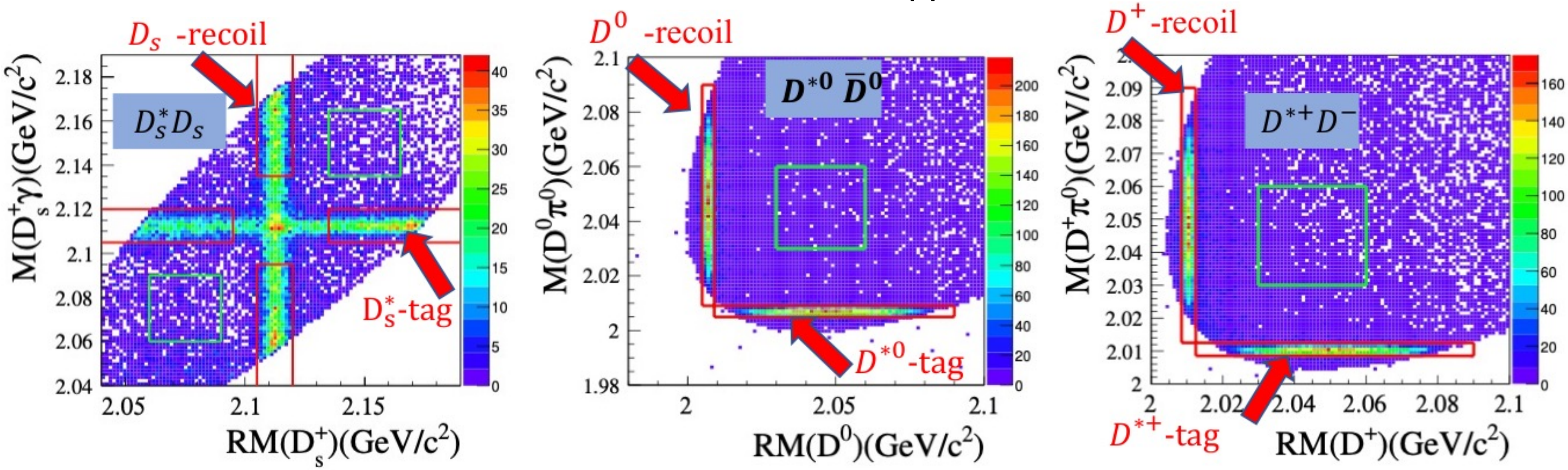
J consistent with 1, value 0 ruled out (NGUYEN 1977).

CHARMED MESONS
($C = \pm1$)
$D^+ = c\bar{d}$, $D^0 = c\bar{u}$, $\overline{D}^0 = \bar{c}u$, $D^- = \bar{c}d$, similarly for D^*'s

$D^*(2010)^\pm$ $I(J^P) = 1/2(1^-)$ I, J, P need confirmation.

Decay chains:

- $e^+e^- \to D_s^{*+}D_s^-, D_s^{*+} \to \gamma D_s^+, D_s^+ \to K_S^0 K^+$
- $e^+e^- \to D^{*0}\overline{D}^0, D^{*0} \to \pi^0 D^0, D^0 \to K^-\pi^+, \pi^0 \to \gamma\gamma$
- $e^+e^- \to D^{*+}D^-, D^{*+} \to \pi^0 D^+, D^+ \to K^-\pi^+\pi^+, \pi^0 \to \gamma\gamma$



Spin and parity of D_s^* meson

- Determination of spin and parity for D_s^* meson. [PLB 846, 138245 (2023)]

- $J^P = 1^-$ for $D_s^{*\pm}$:

$$\mathcal{W}^{(1-)} \sim (3 + cos2\theta_1) - 4cos2\phi_1 sin\theta_0 sin\theta_1$$

- $J^P = 2^+$ for $D_s^{*\pm}$:

$$\mathcal{W}^{(2+)} \sim (3 + cos2\theta_0)(2 + cos2\theta_1 + cos4\theta_1) - 4(1 + 2cos2\theta_1)cos2\phi_1 \sin^2\theta_0 \sin^2\theta_1$$

- $J^P = 3^-$ for $D_s^{*\pm}$:

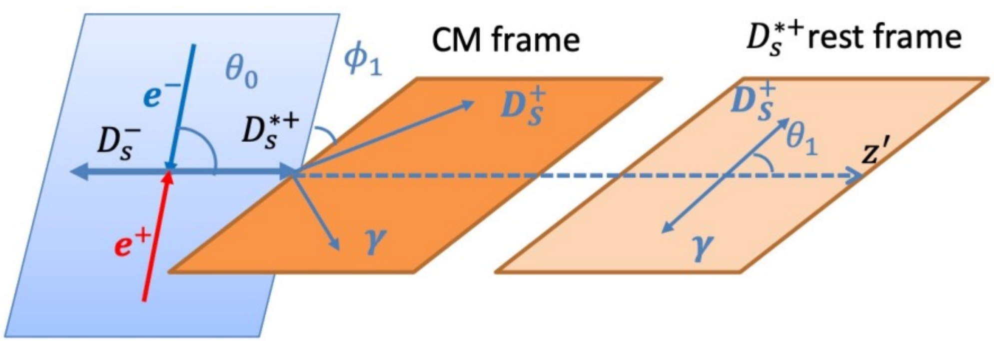
$$\mathcal{W}^{(3-)} \sim (398 + 271cos2\theta_1 + 130cos4\theta_1 + 255cos6\theta_1)$$
$$- 16(163 + 380cos2\theta_0 + 255cos4\theta_0)(163 + 380cos2\theta_1 + 225cos4\theta_1)cos2\phi_1 \sin^2\theta_0 \sin^2\theta_1$$

- Test three possible J^P numbers for $D_s^{*\pm}$

J^P	$e^+e^- \to D_s^{*\pm}D_s^{\mp}$	$D_s^{*\pm} \to \gamma D_s^{\pm}$	$D_s^{*\pm} \to \pi^0 D_s^{\pm}$
0^-	O (Yes)	O (Yes)	× (No)
0^+	×	×	O
1^+	O	O	×
1^-	O[P]	O[P]	O[P]
1^+	O	O	×
2^-	O	O	×
2^+	O[D]	O[D]	O[D]
3^-	O[E]	O[E]	O[E]
3^+	O	O	×

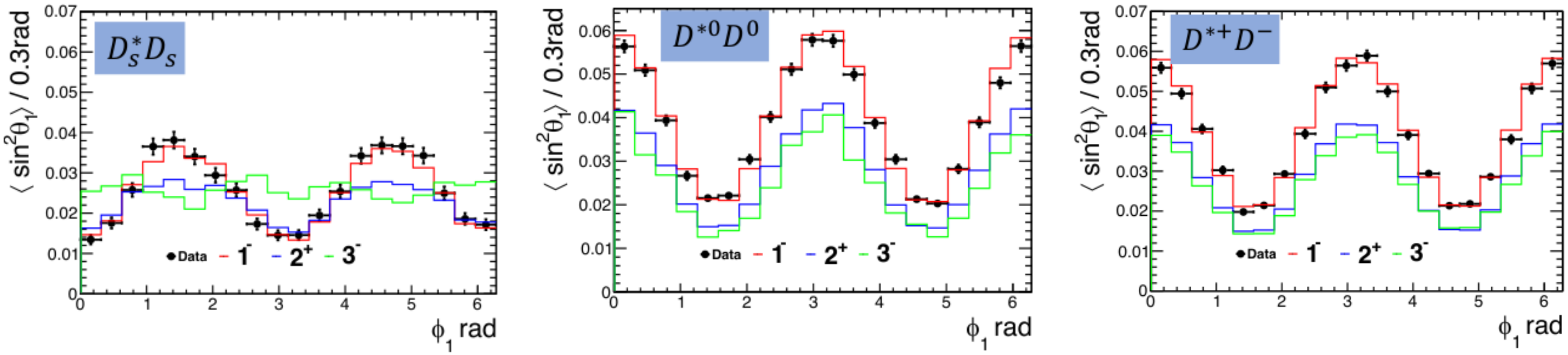
- Exactly same for D^{*0} and D^{*+}

$$\langle \sin^2\theta_1 \rangle \sim \phi_1$$



Spin and parity of D_s^* meson

- Determination of spin and parity for D_s^* meson. [PLB 846, 138245 (2023)]
- Fit result $\langle \sin^2\theta_1 \rangle$ v.s. ϕ_1:



- $\langle \sin^2\theta_1 \rangle$ $v.s.$ ϕ_1 illustrate the different behavior.
- Data obviously favor the 1^- assignment over the 2^+ and 3^-.

- Estimation of statistical significance:

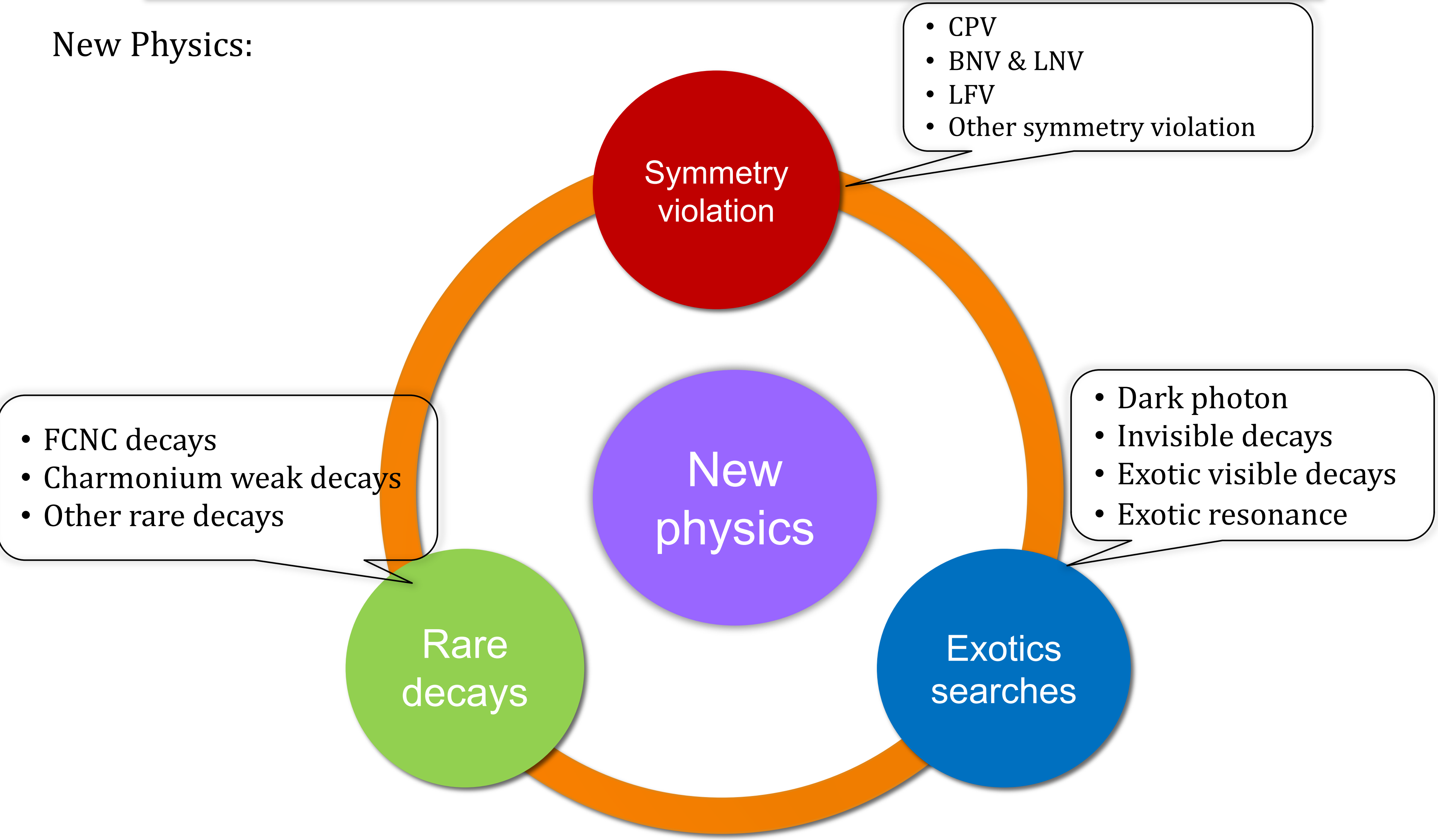
$$S = \sqrt{2(\ln \mathcal{L}_{max}(H_1) - \ln \mathcal{L}_{max}(H_0))}$$

process	$2\lvert\ln\left(\mathcal{L}^{J^P=2^+}/\mathcal{L}^{J^P=1^-,2^+}\right)\rvert$	significance	$2\lvert\ln\left(\mathcal{L}^{J^P=3^-}/\mathcal{L}^{J^P=1^-,3^-}\right)\rvert$	significance
D_s^{*+}	1101.67	$>32\sigma$	2104.36	$>32\sigma$
D^{*0}	29251.08	$>32\sigma$	30989.46	$>32\sigma$
D^{*+}	25672.06	$>32\sigma$	31718.66	$>32\sigma$

The J^P is determined 1^- with large than 32σ significance against 2^+ and 3^- hypotheses.

Recent studies on new physics at BESIII

New Physics:



Recent studies on new physics at BESIII

- Symmetry violation
  - $\Xi^0 \to K^{\pm}e^{\mp}$ (BNV, LNV) : PRD 108, 012006 (2023).
  - $\bar{\Lambda} - \Lambda$ oscillations with $\Delta B = 2$ (BNV) ✓ : PRL 131, 121801 (2023).
  - $D^{\pm} \to n(\bar{n})e^{\pm}$ (BNV, LNV) : PRD 106, 112009 (2022).
  - $D^0 \to pe^-(\bar{p}e^+)$ (BNV, LNV) : PRD 105, 032006 (2022).
  - $J/\psi \to e\mu$ (LFV) ✓ : Sci. China-Phys. Mech. Astron. 66, 221011 (2023).
- Rare decays
  - Search for a massless dark photon in $\Lambda_c^+ \to p\gamma'$(FCNC) ✓ : PRD 106.072008 (2022).
  - Search for $\psi(3686) \to \Lambda_c^+\bar{\Sigma}^- + c.c.$ (Charmonium weak) ✓ : CPC 47, 013002(2023).
  - Search for $J/\psi \to \bar{D}^0(D^-)M$ (Charmonium weak) : arXiv:2310.07277.
  - Search for $J/\psi \to D^-\mu^+\nu_\mu + c.c.$ (Charmonium weak) : arXiv:2307.02165.
- Exotic searches
  - Search for invisible decays of a dark photon ✓ : PLB 839, 137785 (2023).
  - Search for invisible decays of Λ baryon : PRD 105 L071101 (2022).
  - $J/\psi \to \gamma A^0, A^0 \to \mu^+\mu^-$ (Light Higgs) : PRD 105, 012008 (2022).
  - Search for axion-like particles using $\psi(2S)$ data ✓ : PLB 838, 137698 (2023).

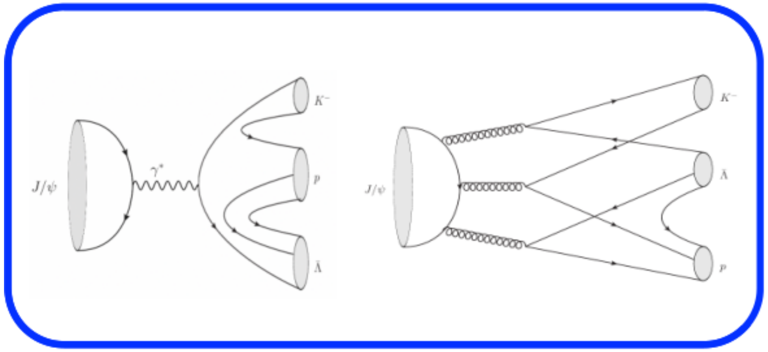
Baryon Number Violation (BNV)

➢ $\bar{\Lambda} - \Lambda$ oscillations with $\Delta B = 2$ [PRL 131, 121801 (2023)]

The time integrated oscillation rate:

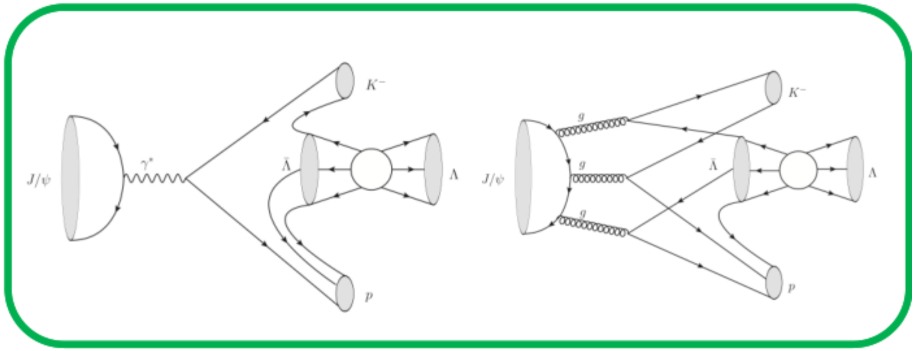
$$J/\psi \to pK^- \bar{\Lambda} \xrightarrow{oscillating} pK^- \Lambda$$

$$\mathcal{P}(\Lambda) = \frac{\int_0^\infty \sin^2(\delta m_{\Lambda\bar{\Lambda}} t) e^{-t/\tau_\Lambda} dt}{\int_0^\infty e^{-t/\tau_\Lambda} dt} \qquad \mathcal{P}(\Lambda) = \frac{\mathcal{B}(J/\psi \to pK^-\Lambda)}{\mathcal{B}(J/\psi \to pK^-\bar{\Lambda})} = \frac{N_{\rm WS}^{obs}/\epsilon_{\rm WS}}{N_{\rm RS}^{obs}/\epsilon_{\rm RS}}$$



Right Sign Channel (Opposite Charge)

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



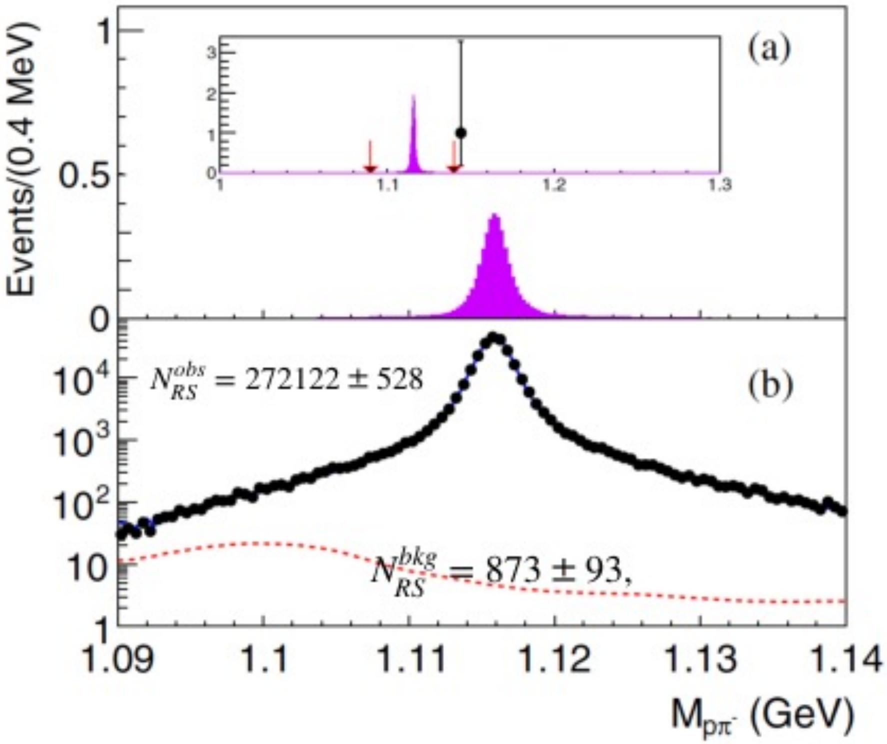
Wrong Sign Channel (Same Charge)

$J/\psi \to pK^-\Lambda \to pK^-(p\pi^-)$

Baryon Number Violation (BNV)

➢ $\bar{\Lambda} - \Lambda$ oscillations with $\Delta B = 2$ [PRL 131, 121801 (2023)]

Fit for $m(p\pi^-)$ of WS and RS:



- Upper limit on oscillation rate (90% CL)

$$P(\Lambda) = \frac{B(J/\psi \to pK^-\Lambda)}{B(J/\psi \to pK^-\bar{\Lambda})} < 4.4 \times 10^{-6}$$

- Oscillation parameter (90% CL)

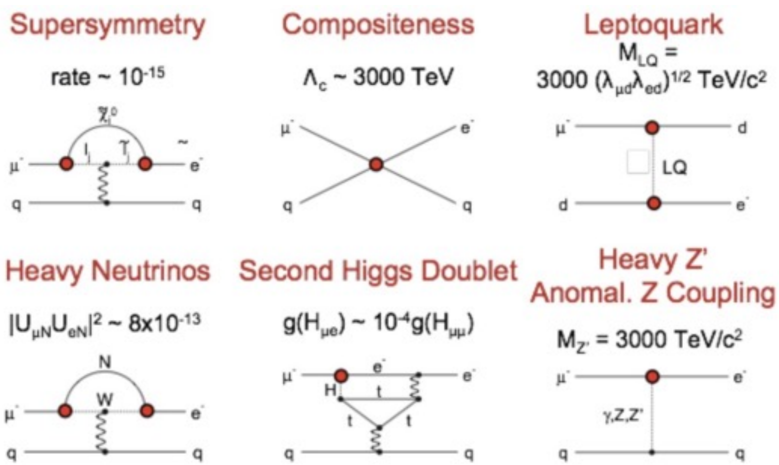
$$\delta m_{\Lambda\bar{\Lambda}} < 3.8 \times 10^{-18} \text{ GeV}$$

- Based on this constraint, the oscillation parameter is calculated to be $\delta m_{\Lambda\bar{\Lambda}} < 3.8 \times 10^{-18}$ GeV at 90% CL corresponding to an oscillation time lower limit of $\tau_{OSC} > 1.7 \times 10^{-7}$ s. This result is comparable with the predicted one in prospect of PRD81,051901 with only about one-tenth data sample.

Lepton Flavor Violation (LFV)

➢ $J/\psi \to e\mu$ [Sci. China-Phys. Mech. Astron. 66, 221011 (2023)]

LFV decay is forbidden in SM, any LFV signals will indicate new physics!



- Different models may enhance LFV effects up to a detectable level, such as leptoquark, compositeness, supersymmetry, heavy Z' and anomalous boson coupling model.

◆ The cLFV decays of vector mesons $V \to l_i l_j$ are also predicted in various of extension models of SM:

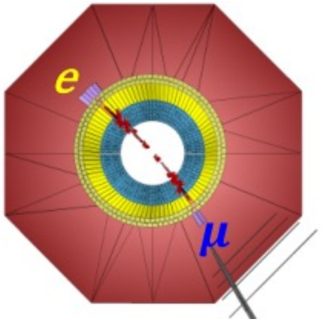
$$\mathcal{B}(J/\psi \to e\mu) \text{ to } 10^{-16} \sim 10^{-9} \text{ @ 90\% C.L.}$$

$$\mathcal{B}(J/\psi \to e(\mu)\tau) \text{ to } 10^{-10} \sim 10^{-8} \text{ @ 90\% C.L.}$$

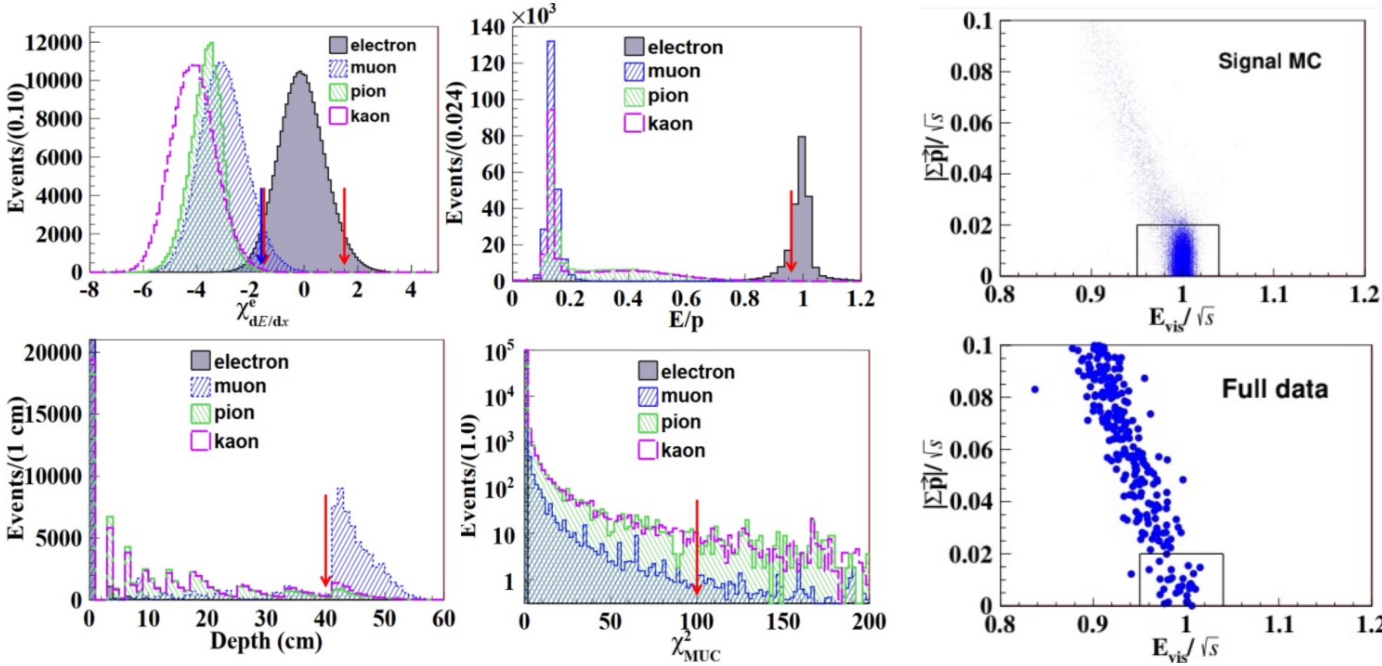
Phys. Rev. D 63, 016003.
Phys. Rev. D 63, 016006
Phys. Rev. D 83, 115015
Phys. Lett. A 27, 1250172
Phys. Rev. D 94, 074023.
Phys. Rev. D 97, 056027

Lepton Flavor Violation (LFV)

➢ $J/\psi \to e\mu$ [Sci. China-Phys. Mech. Astron. 66, 221011 (2023)]



- Special selection criteria to identify e and μ:



- Background subtraction using inclusive MC of J/ψ.
- The signal region is defined with $\frac{|\Sigma\vec{p}|}{\sqrt{s}} \leq 0.02$ and $0.95 \leq \frac{E_{vis}}{\sqrt{s}} \leq 1.04$.

◆ J/ψ MC events → J/ψ decay background (N_{bkg1})

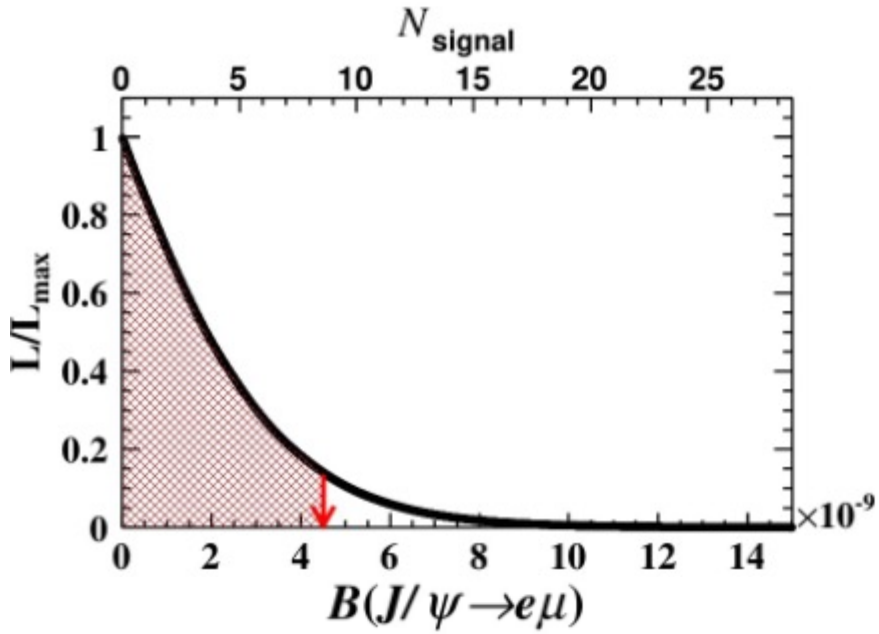
◆ $\psi(3770)$, $\chi_{c1}(1P)$ and 3.080GeV data → Continuum background (N_{bkg2})

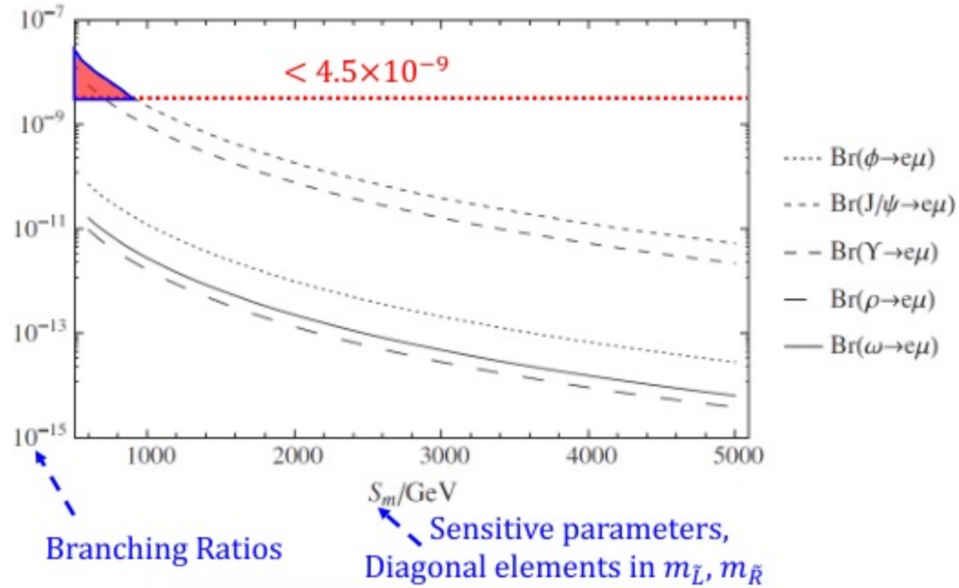
◆ The normalized background is estimated to be $N_{bkg1}^{norm} = 24.8 \pm 1.5$ and $N_{bkg2}^{norm} = 12.0 \pm 3.7$.

Lepton Flavor Violation (LFV)

- $J/\psi \to e\mu$ [Sci. China-Phys. Mech. Astron. 66, 221011 (2023)]

- By analyzing the full data, 29 candidate events are observed, consistent with background estimation.





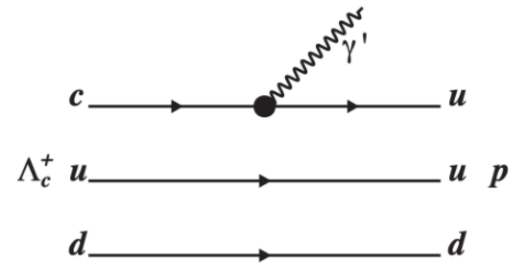
Phys. Rev. D 97, 056027 (2018)

$\mathcal{B}(J/\psi \to e\mu) < 4.5\times10^{-9}$ @ 90% C.L.

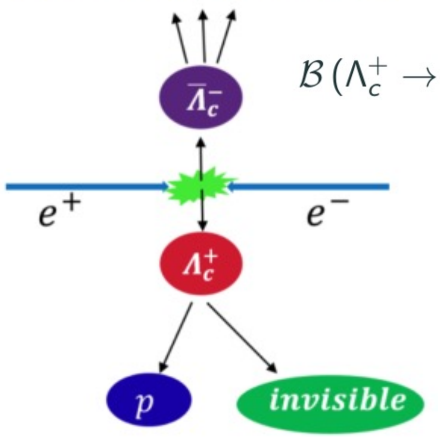
Compared with theoretical predictions, the parameter space of some models, such as BLMSSM model can be excluded.

FCNC decays

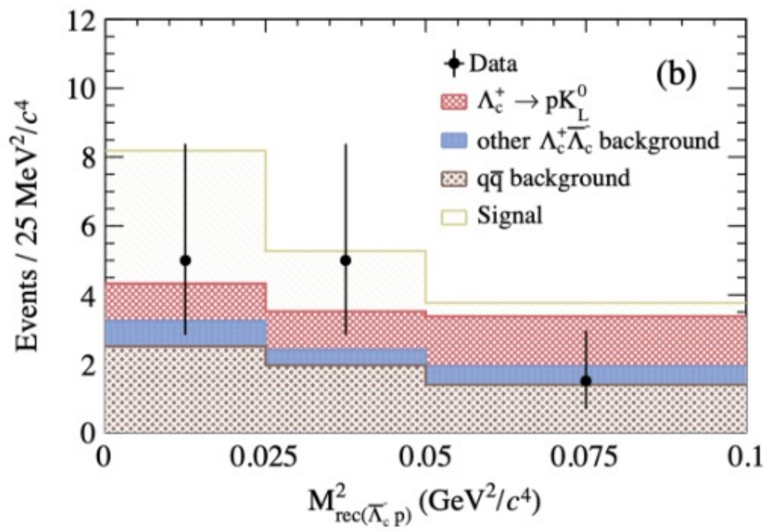
- Search for a massless dark photon in $\Lambda_c^+ \to p\gamma'$ [PRD 106, 072008 (2022)]
  - A spin-one boson associated with a new Abelian gauge symmetry $U(1)_D$
  - FCNC process is highly suppressed by the GIM mechanism in the charm sector
    less than 10^{-9} in SM, Phys. Rev. D 98, 030001 (2018)
  - A massless dark photon could induce FCNC process through higher dimensional operators, allowing $\mathcal{B}(\Lambda_c^+ \to p\gamma')$ up to 1.6×10^{-5}
    Phys. Rev. D 102, 115029 (2020)



10 hadronic decay modes



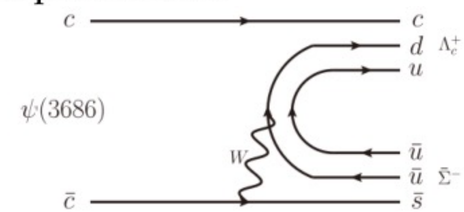
$$\mathcal{B}(\Lambda_c^+ \to p\gamma') = \frac{N_{\rm obs} - N_{\rm bkg}}{\sum_{ij} N_{ij}^{\rm ST} \cdot (\epsilon_{ij}^{\rm DT} / \epsilon_{ij}^{\rm ST})}$$



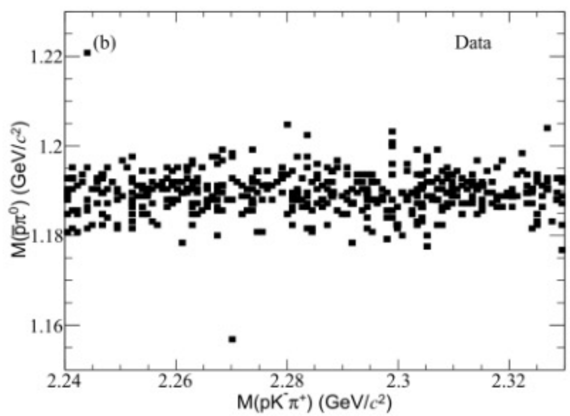
- No significant signal observed, $\mathcal{B}(\Lambda_c^+ \to p\gamma') < 8.0 \times 10^{-5}$ at 90% CL
- Currently consistent with the theoretical UL prediction: 1.6×10^{-5} PRD 102, 115029 (2020)

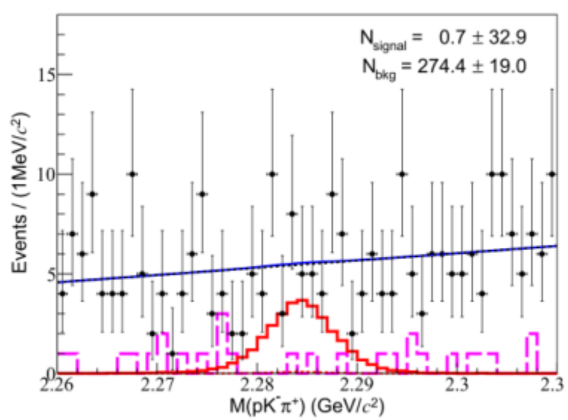
Charmonium weak decays

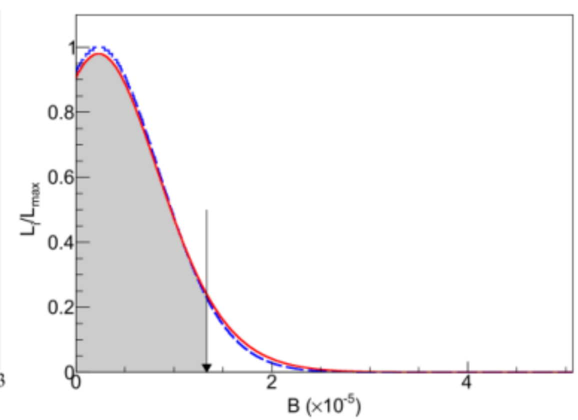
- Search for $\psi(3686) \to \Lambda_c^+ \bar{\Sigma}^- + c.c.$ [CPC 47, 013002(2023)]
  - Searches for purely baryonic weak $\psi(3686)$ decays involving Λ_c^+ have not been performed.
  - In the SM theory, $\mathcal{B}(\psi(3686) \to \Lambda_c^+ \bar{\Sigma}^- + c.c.)$ should be 10^{-9}~10^{-11}.
  - New physics mechanisms beyond the SM may enhance the BF significantly.
  - $\psi(3686) \to \Lambda_c^+ \bar{\Sigma}^-, \Lambda_c^+ \to p K^- \pi^+, \bar{\Sigma}^- \to \bar{p} \pi^0$
  - Two main backgrounds:
    - $\psi(3686) \to K^*(892)^- p \bar{\Lambda},\ \bar{\Lambda} \to \pi^+ \bar{p}$ ⟸ $M(\pi^+ \bar{p})$
    - $\psi(3686) \to \bar{K}^{*0}(892) p \bar{\Sigma}^-,\ \bar{K}^{*0}(892) \to \pi^+ K^-$ ⟸ $M(K^- \pi^+)$



- $\boldsymbol{\mathcal{B}(\psi(3686) \to \Lambda_c^+ \bar{\Sigma}^- + c.c.) < 1.4 \times 10^{-5}}$ **@90% C. L.**



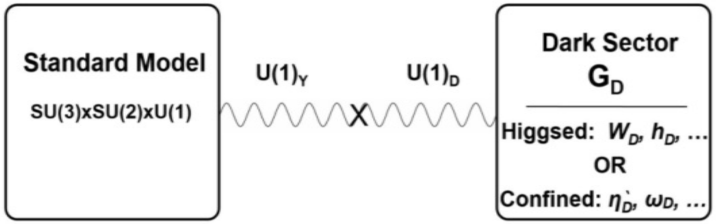


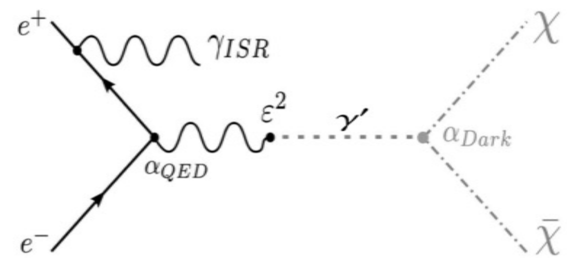


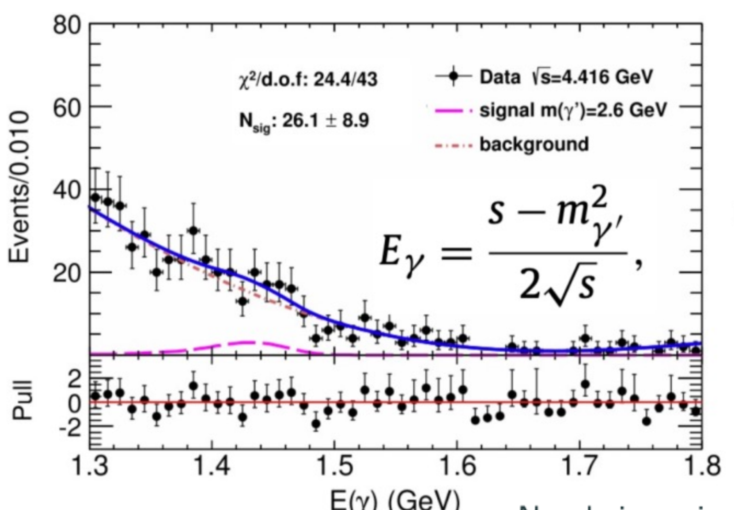
Dark photon

➢ Search for invisible decays of a dark photon [PLB 839, 137785 (2023)]

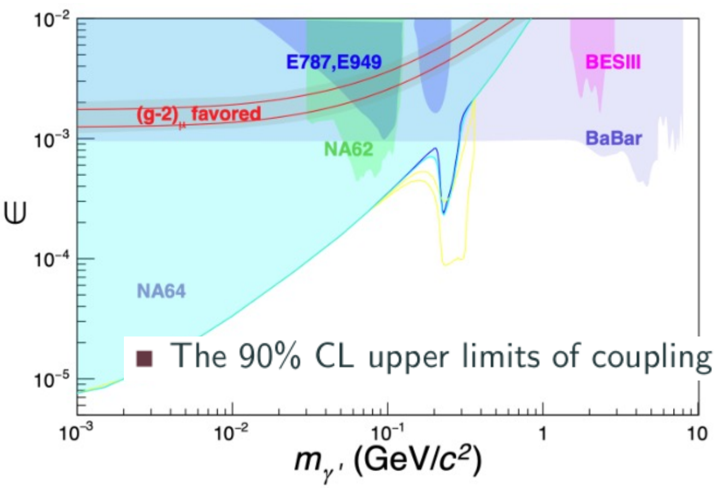
- A spin-one boson associated with a new Abelian gauge symmetry $U(1)_D$ (spontaneously broken, massive kind).
- Proposed as a force carrier connected to dark matter.
- The dark photon couples weakly to a SM photon through kinetic mixing with a mixing parameter $\epsilon \sim 10^{-3}$.
- The dark photon(γ') would predominately decay into a pair of DM particles. ($\gamma' \rightarrow x\bar{x}$)
- Search for the dark photon in the radiative annihilation process $e^+e^- \rightarrow \gamma\gamma'$, followed by an invisible decay of γ'.







$$E_\gamma = \frac{s - m_{\gamma'}^2}{2\sqrt{s}},$$

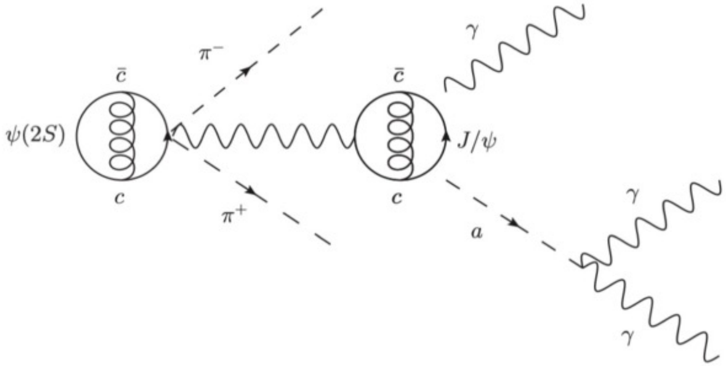


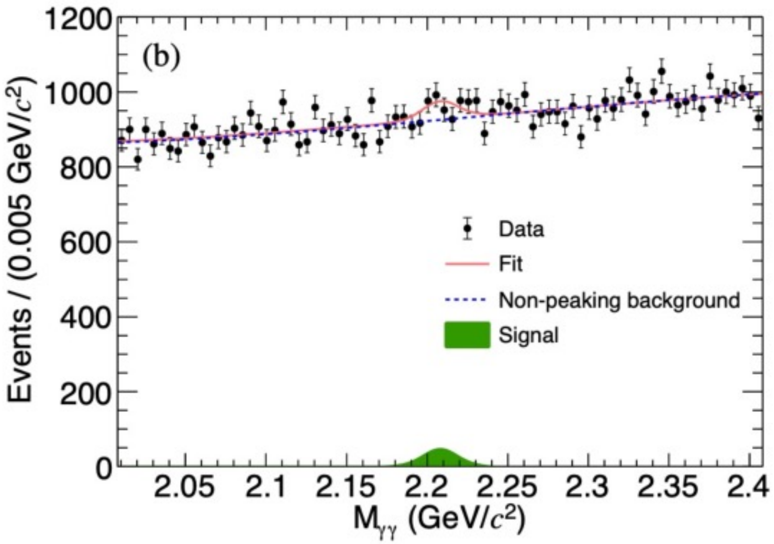
- The 90% CL upper limits of coupling ϵ are $(1.6 - 5.7) \times 10^{-3}$
- No obvious signal observed, the the maximum global significance, is determined to be 2.2σ

Axion-like particles

- Search for axion-like particles using $\psi(2S)$ data [PLB 838, 137698 (2023)]

- Axion-like particle "a" has negligible decay width and lifetime in $0.165 \leq m_a \leq 2.84\ \mathrm{GeV}/c^2$.
- $\psi(3686)$ decay -> preclude the pollution from non-resonant production and avoid QED background.
- Three $\gamma\gamma$ combinations per event, exclude intervals around π^0, η, η′ peaks.





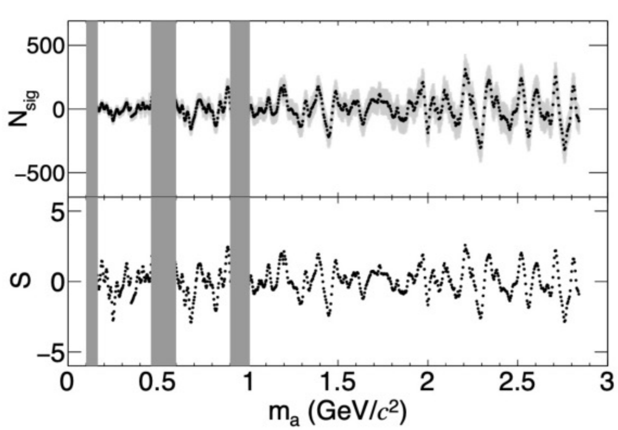
$$\frac{\mathcal{B}(J/\psi \to \gamma a)}{\mathcal{B}(J/\psi \to e^+e^-)} = \frac{m_{J/\psi}^2}{32\pi\alpha} g_{a\gamma\gamma}^2 \left(1 - \frac{m_a^2}{m_{J/\psi}^2}\right)^3$$

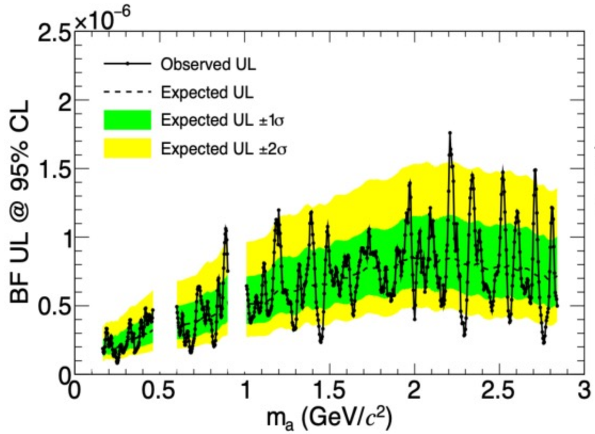
- Fits are performed to the $M(\gamma\gamma)$ in the mass range of $0.165 \leq m_a \leq 2.84\ \mathrm{GeV}/c^2$.

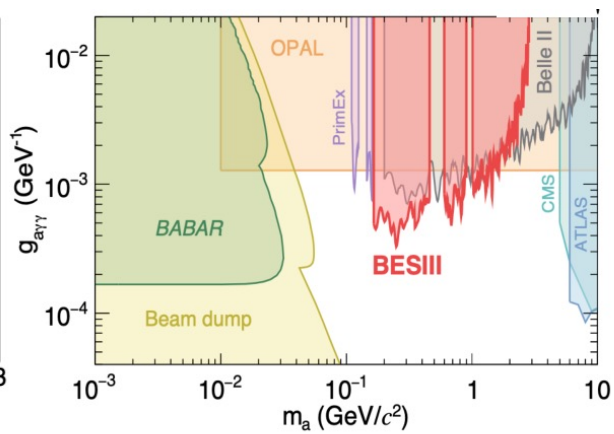
Axion-like particles

➢ Search for axion-like particles using $\psi(2S)$ data [PLB 838, 137698 (2023)]

- Totally, 674 mass hypotheses are probed, exclude intervals around π^0, η, η′ peaks.
- The local significance are less than 2.6σ for all mass points.





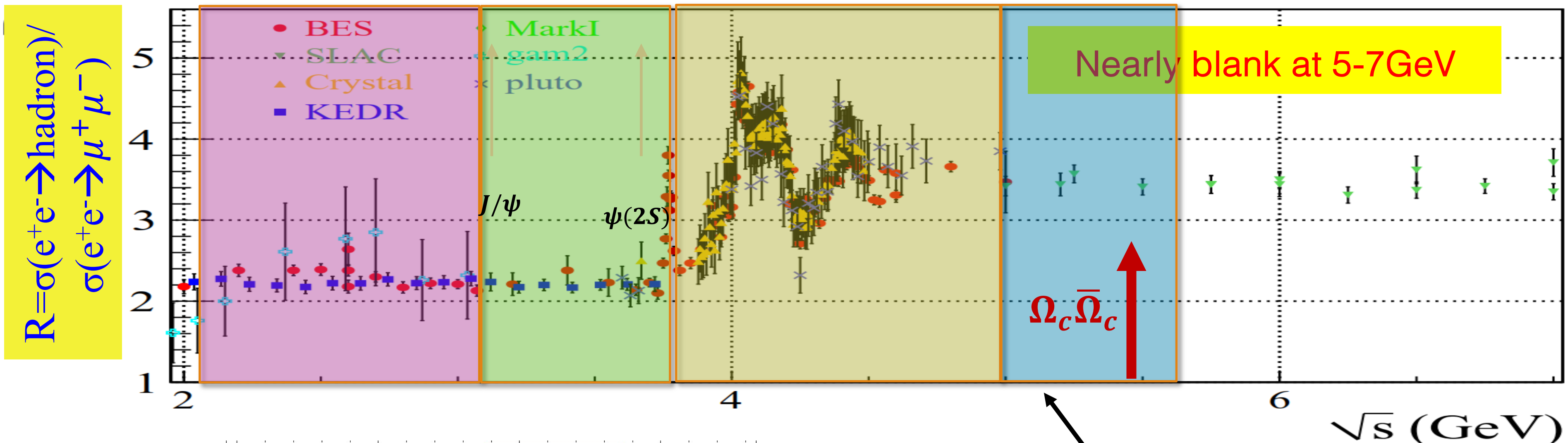


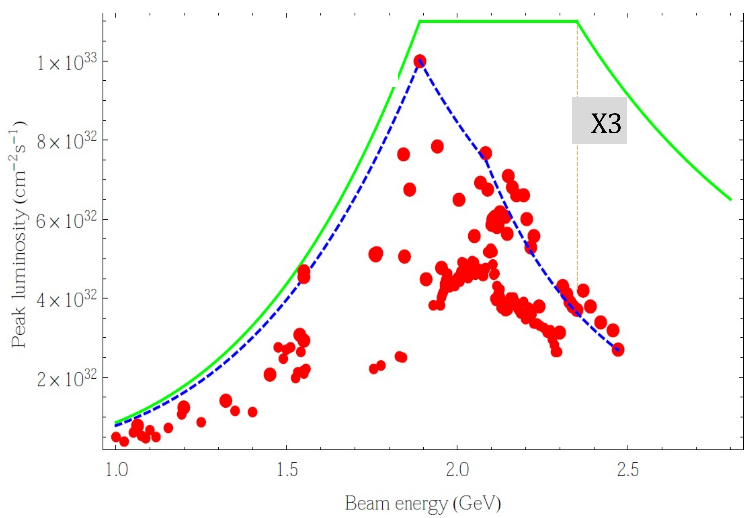
$$g_{a\gamma\gamma} = \sqrt{\frac{\mathcal{B}(J/\psi \to \gamma a)}{\mathcal{B}(J/\psi \to e^+e^-)}(1 - \frac{m_a^2}{m_{J/\psi}^2})^{-3}\frac{32\pi\alpha_{\rm em}}{m_{J/\psi}^2}}$$

- Upper limits on $B(J/\psi \to \gamma a)$ at 95% confidence level are determined based on a one-sided frequentist profile-likelihood method [Eur. Phys. J. C 71, 1554 (2011)], the observed limits range from 8.3×10^{-8} to 1.8×10^{-6} in $0.165 \le m_a \le 2.84$ GeV/c^2.
- The exclusion limits on the ALP-photon coupling are the most stringent to date.

Proposal of the BEPCII upgrade

- optimized energy at 2.35 GeV with luminosity 3 times higher than the current BEPCII.





4.95 ~ 5.6 GeV: new energy coverage of BEPCII-upgrade

Energy thresholds

✓	$\Lambda_c^+\bar{\Sigma}_c^-$	4.74 GeV
✓	$\Lambda_c^+\bar{\Sigma}_c\ \pi$	4.88 GeV
✓	$\Sigma_c\ \bar{\Sigma}_c$	4.91 GeV
✓	$\Xi_c\ \bar{\Xi}_c$	4.95 GeV
✓	$\Omega_c^0\bar{\Omega}_c^0$	5.4 GeV

Prospect Charm Baryons data sample at BESIII

Table 7.1. List of data samples collected by BESIII/BEPCII up to 2019, and the proposed samples for the remainder of the physics program. The right-most column shows the number of required data taking days with the current (T_C) and upgraded (T_U) machine. The machine upgrades include top-up implementation and beam current increase.

Energy	Physics motivations	Current data	Expected final data	T_C / T_U
1.8 - 2.0 GeV	R values Nucleon cross-sections	N/A	0.1 fb^{-1} (fine scan)	60/50 days
2.0 - 3.1 GeV	R values Cross-sections	Fine scan (20 energy points)	Complete scan (additional points)	250/180 days
J/ψ peak	Light hadron & Glueball J/ψ decays	3.2 fb^{-1} (10 billion)	3.2 fb^{-1} (10 billion)	N/A
$\psi(3686)$ peak	Light hadron & Glueball Charmonium decays	0.67 fb^{-1} (0.45 billion)	4.5 fb^{-1} (3.0 billion)	150/90 days
$\psi(3770)$ peak	$D^0/D^\pm$ decays	2.9 fb^{-1}	20.0 fb^{-1}	610/360 days
3.8 - 4.6 GeV	R values XYZ/Open charm	Fine scan (105 energy points)	No requirement	N/A
4.180 GeV	D_s decay XYZ/Open charm	3.2 fb^{-1}	6 fb^{-1}	140/50 days
4.0 - 4.6 GeV	XYZ/Open charm Higher charmonia cross-sections	16.0 fb^{-1} at different $\sqrt{s}$	30 fb^{-1} at different $\sqrt{s}$	770/310 days
4.6 - 4.9 GeV	Charmed baryon/XYZ cross-sections	0.56 fb^{-1} at 4.6 GeV	15 fb^{-1} at different $\sqrt{s}$	1490/600 days
4.74 GeV	$\Sigma_c^+\bar{\Lambda}_c^-$ cross-section	N/A	1.0 fb^{-1}	100/40 days
4.91 GeV	$\Sigma_c\bar{\Sigma}_c$ cross-section	N/A	1.0 fb^{-1}	120/50 days
4.95 GeV	Ξ_c decays	N/A	1.0 fb^{-1}	130/50 days

Summary

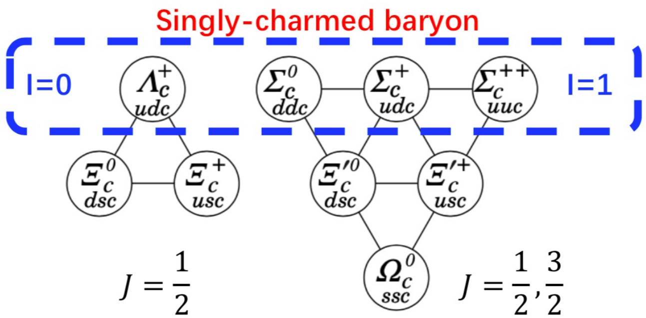
- BEPCII energy upgrade during 2020-2021 has improved the BESIII capability by accumulating more statistics at different energy points.
- BESIII has been playing significant role in studying flavor physics of charm sector and searching for new physics. Many new important results have been published during 2023.
- Future STCF will greatly extend the physics opportunities in study of flavor physics and search for new physics!

Thanks!

Backup

Energy thresholds

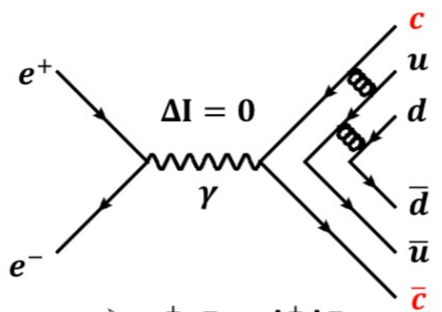
- ✓ $e^+e^- \to \Lambda_c^+\bar{\Sigma}_c^-$ 4.74~4.87 GeV
- ✓ $e^+e^- \to \Lambda_c^+\bar{\Lambda}_c^-(2595)(\bar{\Sigma}_c\ \pi)$ 4.88 GeV
- ✓ $e^+e^- \to \Sigma_c\ \bar{\Sigma}_c$ 4.91 GeV
- ✓ $e^+e^- \to \Xi_c\ \bar{\Xi}_c$ 4.95 GeV



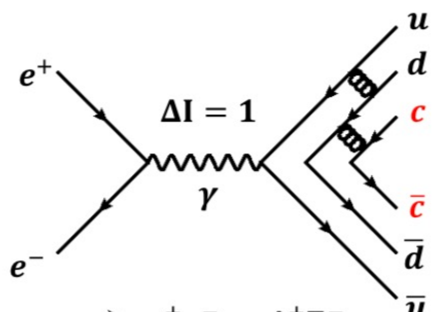
The Born cross-section **ratios** between $\Lambda_c^+\Lambda_c^- + c.c.$ and $\Lambda_c^-\Sigma_c^+ + c.c.$ at different energy points can provide more information about the production of $c\bar{c}$ or $q\bar{q}$ from vacuum.

BESIII Cross sections for $e^+e^- \to \Lambda_c^+\bar{\Sigma}_c^-$ and $\Sigma_c\ \bar{\Sigma}_c$

- **$e^+e^- \to \Lambda_c^+\bar{\Sigma}_c^-$ above 4.74 GeV:** An interesting isospin violating process to understand the QCD dynamics at charm sector
  - ✓ A cross section scan slightly above 4.74 GeV will be useful for comparison with that of $e^+e^- \to \Lambda_c^+\bar{\Lambda}_c^-$ and $\Lambda_c^+\bar{\Sigma}_c^-$
  - ✓ $\sigma(\Lambda_c^+\bar{\Sigma}_c^-)/\sigma(\Lambda_c^+\bar{\Lambda}_c^-)$ v.s. $\sigma(\Lambda\bar{\Sigma})/\sigma(\Lambda\bar{\Lambda})$
    ➔ vaccum pol. to $c\bar{c}$ v.s. $s\bar{s}$
  - ✓ If observed, study the polarizations and form factors
- **$e^+e^- \to \Sigma_c\ \bar{\Sigma}_c$ around 4.91 GeV:**
  - ✓ Cross section comparison with that of $e^+e^- \to \Lambda_c^+\bar{\Lambda}_c^-$
    ➔ good diquark v.s. bad diquark
  - ✓ Study the polarizations and form factors in $e^+e^- \to \Sigma_c^0\bar{\Sigma}_c^0$ and $\Sigma_c^+\bar{\Sigma}_c^-$



➢ $e^+e^- \to \Lambda_c^+\Lambda_c^-$



➢ $e^+e^- \to \Lambda_c^+\Sigma_c^-$

Production measurement near threshold

PhysRevLett.131.191901(2023)

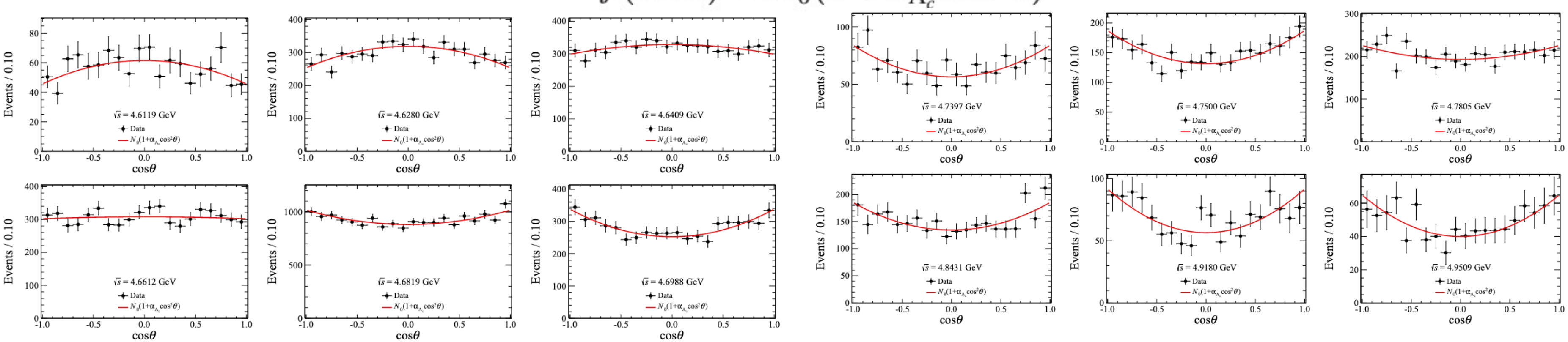
- $e^+e^- \to \Lambda_c^+ \Lambda_c^-$ cross section are measured at twelve energy points from 4.612-4.951GeV .

$\sqrt{s}$ (GeV)	$\mathcal{L}_{\rm int}$ (pb^{-1})	σ (pb)	$\lvert G_{\rm eff}\rvert$ (10^{-2})	α_{Λ_c}	$\lvert G_E/G_M\rvert$	$\lvert G_M\rvert$ (10^{-2})
4.6119	103.7	$208.4 \pm 6.9 \pm 7.0$	$49.2 \pm 0.8 \pm 0.8$	$-0.26 \pm 0.09 \pm 0.01$	$1.31 \pm 0.12 \pm 0.01$	$43.5 \pm 3.3 \pm 1.5$
4.6280	521.5	$206.4 \pm 3.1 \pm 6.9$	$45.5 \pm 0.3 \pm 0.8$	$-0.21 \pm 0.04 \pm 0.01$	$1.25 \pm 0.06 \pm 0.01$	$41.8 \pm 1.5 \pm 1.5$
4.6409	551.6	$205.1 \pm 3.0 \pm 6.9$	$43.4 \pm 0.3 \pm 0.7$	$-0.09 \pm 0.05 \pm 0.01$	$1.11 \pm 0.05 \pm 0.01$	$41.8 \pm 1.4 \pm 1.4$
4.6612	529.4	$200.3 \pm 2.9 \pm 6.8$	$40.6 \pm 0.3 \pm 0.7$	$-0.02 \pm 0.05 \pm 0.01$	$1.04 \pm 0.05 \pm 0.01$	$40.2 \pm 1.4 \pm 1.4$
4.6819	1667.4	$188.1 \pm 1.6 \pm 6.3$	$37.7 \pm 0.2 \pm 0.6$	$0.15 \pm 0.03 \pm 0.01$	$0.88 \pm 0.03 \pm 0.01$	$39.2 \pm 0.8 \pm 1.3$
4.6988	535.5	$172.3 \pm 2.7 \pm 6.0$	$35.1 \pm 0.3 \pm 0.6$	$0.34 \pm 0.07 \pm 0.01$	$0.72 \pm 0.06 \pm 0.01$	$38.2 \pm 1.4 \pm 1.3$
4.7397	163.9	$123.5 \pm 4.2 \pm 5.0$	$28.2 \pm 0.5 \pm 0.6$	$0.49 \pm 0.16 \pm 0.03$	$0.61 \pm 0.13 \pm 0.02$	$31.4 \pm 2.4 \pm 1.3$
4.7500	366.6	$128.5 \pm 2.8 \pm 4.4$	$28.5 \pm 0.3 \pm 0.5$	$0.42 \pm 0.10 \pm 0.01$	$0.66 \pm 0.08 \pm 0.01$	$31.4 \pm 1.6 \pm 1.1$
4.7805	511.5	$124.0 \pm 2.4 \pm 4.2$	$27.2 \pm 0.3 \pm 0.5$	$0.17 \pm 0.07 \pm 0.01$	$0.88 \pm 0.07 \pm 0.01$	$28.2 \pm 1.2 \pm 1.0$
4.8431	525.2	$84.8 \pm 2.0 \pm 2.9$	$21.6 \pm 0.3 \pm 0.4$	$0.38 \pm 0.10 \pm 0.01$	$0.71 \pm 0.09 \pm 0.01$	$23.4 \pm 1.3 \pm 0.8$
4.9180	207.8	$98.1 \pm 3.3 \pm 3.5$	$22.4 \pm 0.4 \pm 0.4$	$0.62 \pm 0.17 \pm 0.01$	$0.52 \pm 0.15 \pm 0.01$	$25.3 \pm 1.9 \pm 0.9$
4.9509	159.3	$89.6 \pm 3.6 \pm 3.1$	$21.2 \pm 0.4 \pm 0.4$	$0.63 \pm 0.21 \pm 0.01$	$0.52 \pm 0.18 \pm 0.01$	$24.1 \pm 2.2 \pm 0.9$

$$\alpha_{\Lambda_c} = \frac{1 - \kappa R^2}{1 + \kappa R^2}.$$

$$R = |G_E/G_M|$$

$$f(\cos\theta) = N_0(1 + \alpha_{\Lambda_c} \cos^2\theta)$$



Coming soon stay tunned

- $\Lambda_c^+ \to n e^+ \nu_e$(release soon)
- $\Lambda_c^+ \to \Sigma^+ \pi^- e^+ \nu_e$、 $\Sigma^- \pi^+ e^+ \nu_e$
- $\Lambda_c^+ \to p \pi^- e^+ \nu_e$
- $\Lambda_c^+ \to n K_s^0 e^+ \nu_e$

- $\Lambda_c^+ \to p K_L^0$、 $p\phi$
- $\Lambda_c^+ \to p K_s^0$、 $\Lambda\pi^+$、 $\Sigma^0\pi^+$、 $\Sigma^+\pi^0$(Decay asymmetry and polarization study)

- $\Lambda_c^+ \to n K^+ \pi^0$(DCS)
- $\Lambda_c^+ \to p K^- \pi^+$、 $p K_S^0 \pi^0$、 $p K_L^0 \pi^0$
- $\Lambda_c^+ \to \Lambda K_s^0 K^+$、$\Lambda K_s^0 \pi^+ (\Lambda K^{*+})$
- $\Lambda_c^+ \to \Sigma^0 \pi^+ \pi^0$、 $\Sigma^+ \pi^+ \pi^-$ 、 $\Sigma^- \pi^+ \pi^+$
- $\Lambda_c^+ \to \Sigma^+ K^+ K^+ \ (\phi)$、 $\Sigma^+ K^+ \pi^- (\pi^0)$、 $\Sigma^0 K_s^0 K^+$、
- $\Lambda_c^+ \to \Xi^- K^+ \pi^+$、$\Xi^0 K_s^0 K^+$

- $\Lambda_c^+ \to p K^- \pi^+ \pi^0$ 、 $p K_L^0 \pi^+ \pi^-$

- $\Lambda_c^+ \to \Lambda X$、$K_s^0 X$、$pX$