

BESIII实验上的粲强子单举衰变研究

肖栋·兰州大学

2026年BESIII粲强子物理研讨会，成都

2026年10月17日

Outline

- Introduction to inclusive decay
- Inclusive semi-leptonic decay
- Inclusive hadronic decay
- Summary & prospect



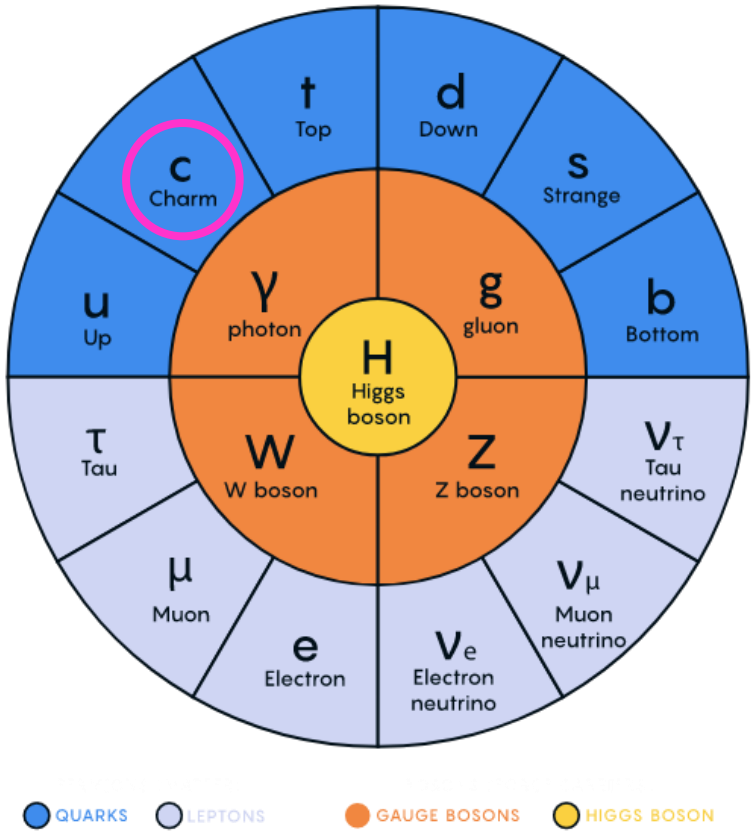


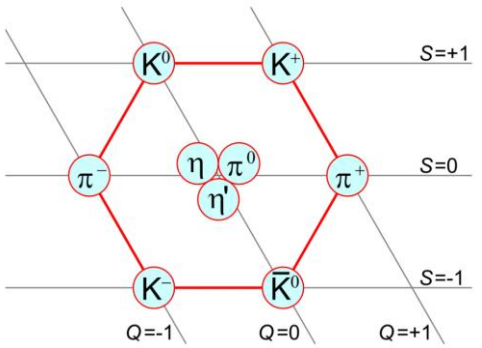
Chapter 1

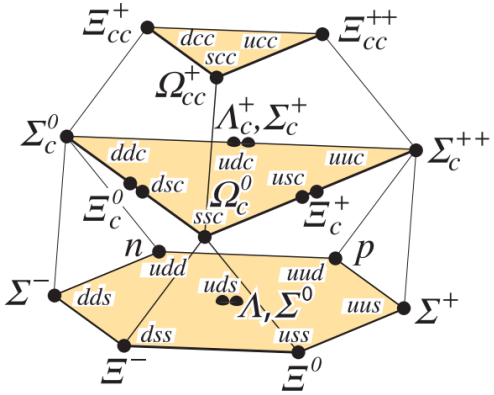
Introduction to inclusive decay

Standard model

- Standard Model (SM):







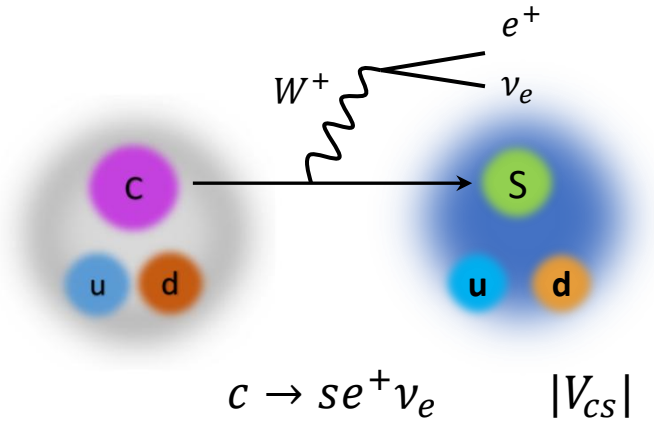
Success and shortage of SM:

- ✓ A good framework of particle physics based on 3 interactions and 61 basic particles;
- ✓ Agreement well with many experiments;
- ✓ Successful predictions.

- No gravity;
- Parameters;
- CP violation;
- Neutrino oscillation;
- QCD non-perturbative; => Important question!
- ...

What is inclusive decay?

- **Inclusive decay:**
- Decay as $A \to B + X$, B is a certain particle, X contains any possible particles, then this decay is called an inclusive decay of particle A;
- Inclusive decay is the sum of a series of exclusive decays。



$c \to se^+\nu_e$ $\quad |V_{cs}|$

- **Motivation:**
- Guide for undiscovered exclusive decays;
- Provide verifications for SM predictions;
- Extract parameters for theoretical studies.

- **Research objects:**
- BF
- Decay parameter α
- CPV
- CKM parameter
- HQE non-perturbative parameter...

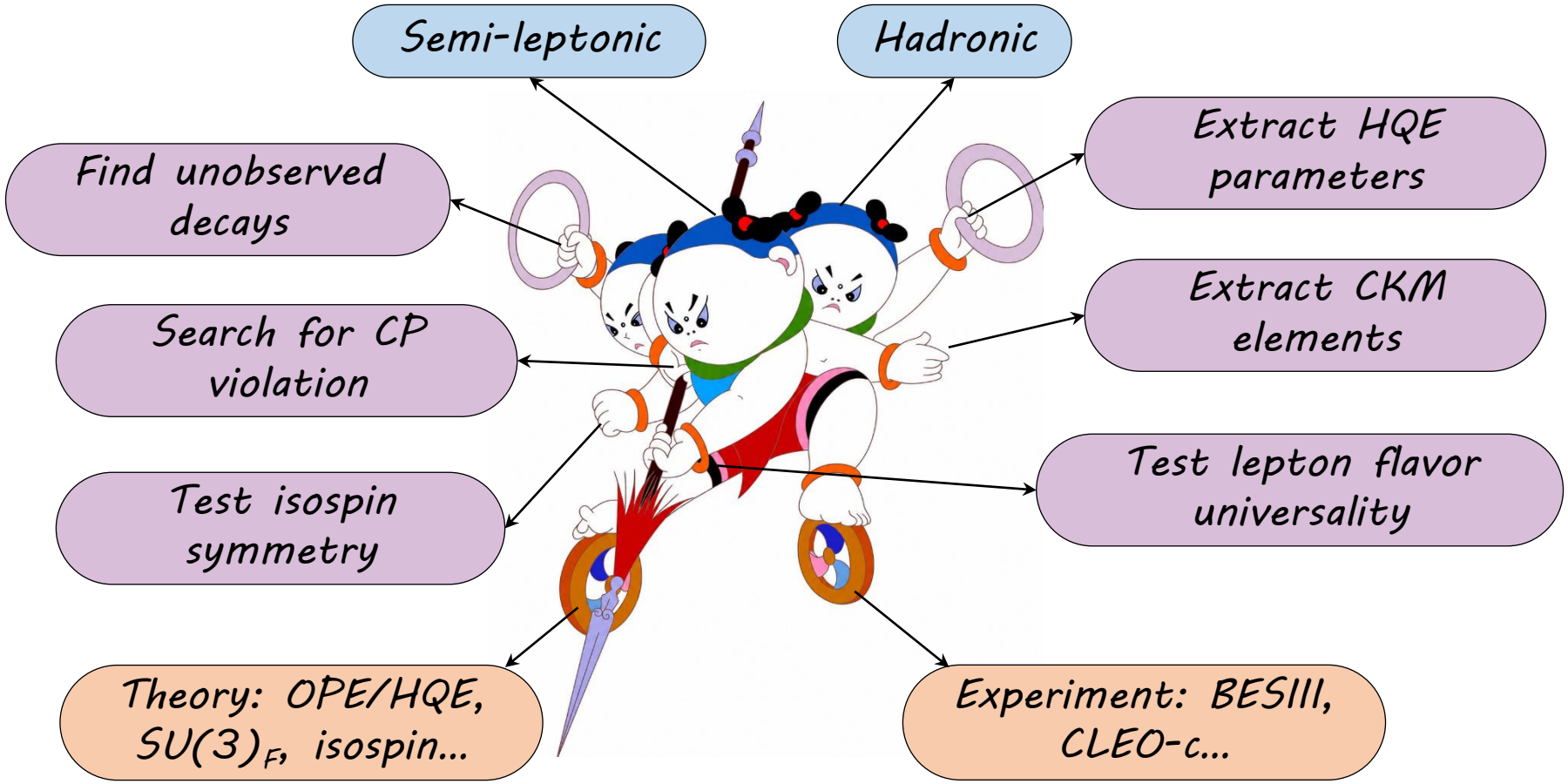
$$\mathcal{B}_{exclusive}(\Lambda_c^+ \to \Lambda X) \approx (33.59 \pm 1.09)\%$$

$$\mathcal{B}_{inclusive}(\Lambda_c^+ \to \Lambda X) = (38.07 \pm 0.38 \pm 0.49)\%$$

=> Any other decay modes?

Why inclusive decay

- Why study inclusive decays of charm hadron?



Status of inclusive decay

- D^+:

▾ **Inclusive modes**

Γ_1	e^+ semileptonic	CLEO,2010	$(16.07 \pm 0.30)\,\%$
Γ_2	μ^+ anything	BES2,2008	$(17.6 \pm 3.2)\,\%$
Γ_3	K^- anything	BES2,2007	$(25.7 \pm 1.4)\,\%$
Γ_4	K_S^0 anything	BES3,2023	$(33.1 \pm 0.4)\,\%$
Γ_5	K^+ anything	BES2,2007	$(5.9 \pm 0.8)\,\%$
Γ_6	$K^*(892)^-$ anything	BES2,2006	$(6 \pm 5)\,\%$
Γ_7	$\overline{K}^*(892)^0$ anything	BES,2005	$(23 \pm 5)\,\%$
Γ_8	$K^*(892)^0$ anything	BES,2005	$<6.6\,\%$
Γ_9	η anything	CLEO,2006	$(6.3 \pm 0.7)\,\%$
Γ_{10}	η' anything	CLEO,2006	$(1.04 \pm 0.18)\,\%$
Γ_{11}	ϕ anything	BES3,2019	$(1.12 \pm 0.04)\,\%$
Γ_{12}	$\pi^+\pi^+\pi^-$ anything	BES3,2023	$(15.25 \pm 0.20)\,\%$

- D^0:

▾ **Inclusive modes**

Γ_5	e^+ anything	CLEO,2010	[6]	$(6.49 \pm 0.11)\,\%$
Γ_6	μ^+ anything	BES2,2008		$(6.8 \pm 0.6)\,\%$
Γ_7	K^- anything	BES2,2007		$(54.7 \pm 2.8)\,\%$
Γ_8	K_S^0 anything	BES3,2023		$(20.75 \pm 0.23)\,\%$
Γ_9	K^+ anything	BES2,2007		$(3.4 \pm 0.4)\,\%$
Γ_{10}	$K^*(892)^-$ anything	BES2,2006		$(15 \pm 9)\,\%$
Γ_{11}	$\overline{K}^*(892)^0$ anything	BES,2005		$(9 \pm 4)\,\%$
Γ_{12}	$K^*(892)^+$ anything	BES2,2006		$<3.6\,\%$
Γ_{13}	$K^*(892)^0$ anything	BES,2005		$(2.8 \pm 1.3)\,\%$
Γ_{14}	η anything	CLEO,2006		$(9.5 \pm 0.9)\,\%$
Γ_{15}	η' anything	CLEO,2006		$(2.48 \pm 0.27)\,\%$
Γ_{16}	ϕ anything	BES3,2019		$(1.08 \pm 0.04)\,\%$
Γ_{17}	$\pi^+\pi^+\pi^-$ anything	BES3,2023		$(17.60 \pm 0.25)\,\%$

- Λ_c^+:

▾ **Inclusive modes**

Γ_{116}	e^+ anything	$(4.06 \pm 0.13)\,\%$	→ BESIII, 2018, 2023
Γ_{117}	p anything	$(50 \pm 16)\,\%$	→ BESIII, on-going
Γ_{118}	n anything	$(32.6 \pm 1.6)\,\%$	→ BESIII, 2023
Γ_{119}	Λ anything	$(38.2^{+2.9}_{-2.4})\,\%$	→ BESIII, 2018, 2026
Γ_{120}	K_S^0 anything	$(10.90 \pm 0.22)\,\%$	→ BESIII, 2025
Γ_{121}	3prongs	$(24 \pm 8)\,\%$	→ CHRS, 2003

Status of inclusive decay

- D_s^+:

▾ Inclusive modes

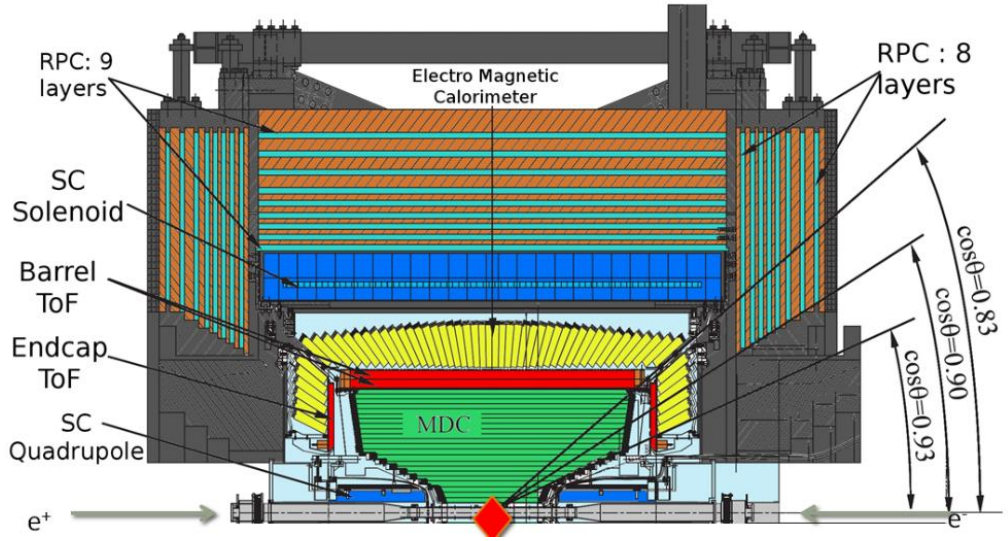
Γ_1	e^+ semileptonic	BES3,2021	[1]	$(6.33 \pm 0.15)\%$
Γ_2	π^+ anything	CLEO,2009		$(119.3 \pm 1.4)\%$
Γ_3	π^- anything	CLEO,2009		$(43.2 \pm 0.9)\%$
Γ_4	π^0 anything	CLEO,2009		$(123 \pm 7)\%$
Γ_5	K^- anything	CLEO,2009		$(18.7 \pm 0.5)\%$
Γ_6	K^+ anything	CLEO,2009		$(28.9 \pm 0.7)\%$
Γ_7	K_S^0 anything	CLEO,2009		$(19.0 \pm 1.1)\%$
Γ_8	η anything	CLEO,2009	[2]	$(29.9 \pm 2.8)\%$
Γ_9	ω anything	CLEO,2009		$(6.1 \pm 1.4)\%$
Γ_{10}	η' anything	BES3,2015	[3]	$(10.3 \pm 1.4)\%$
Γ_{11}	$f_0(980)$ anything, $f_0 \to \pi^+\pi^-$	CLEO,2009		$< 1.3\%$
Γ_{12}	ϕ anything	CLEO,2009		$(15.7 \pm 1.0)\%$
Γ_{13}	K^+K^- anything	CLEO,2009		$(15.8 \pm 0.7)\%$
Γ_{14}	$K_S^0\,K^+$ anything	CLEO,2009		$(5.8 \pm 0.5)\%$
Γ_{15}	$K_S^0\,K^-$ anything	CLEO,2009		$(1.9 \pm 0.4)\%$
Γ_{16}	2 K_S^0 anything	CLEO,2009		$(1.70 \pm 0.32)\%$
Γ_{17}	2 K^+ anything	CLEO,2009		$< 2.6 \times 10^{-3}$
Γ_{18}	2 K^- anything	CLEO,2009		$< 6 \times 10^{-4}$

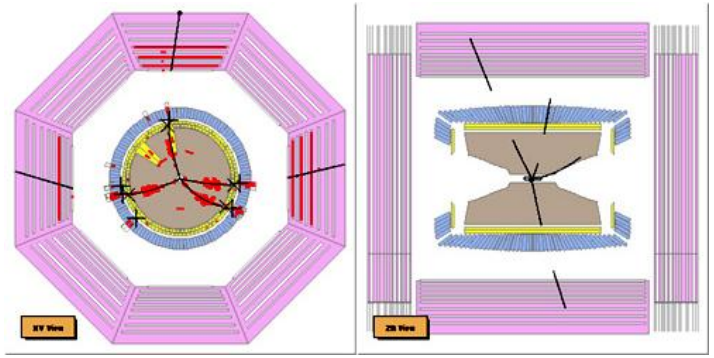
BEPCII & BESIII

- BEPCII:

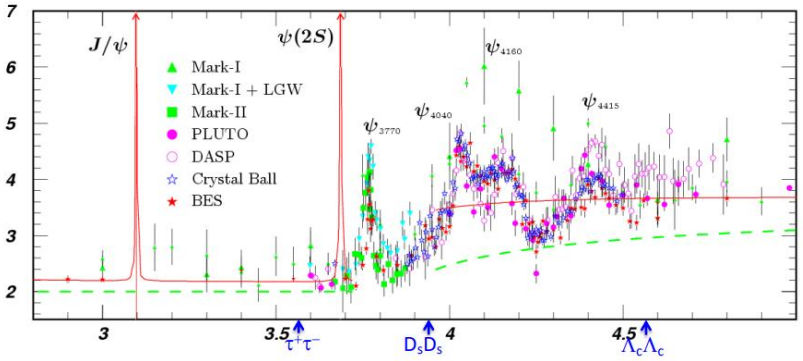


BESIII:









BEPC: China's first HEP collider(1988)
BEPCII: Upgrade (2008)
Center-of-mass energy: 2 ~ 5 GeV
Max luminosity: $1\times10^{33}cm^{-2}s^{-1}$

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

J/ψ : 2·97 fb^{-1}(10B)
$\psi(3686)$: 4·07 fb^{-1}(2·7B)
$\psi(3770)$: 20·3 fb^{-1}
4·6 ~ 4·95 GeV: 6·4 fb^{-1}

Inclusive at BESIII

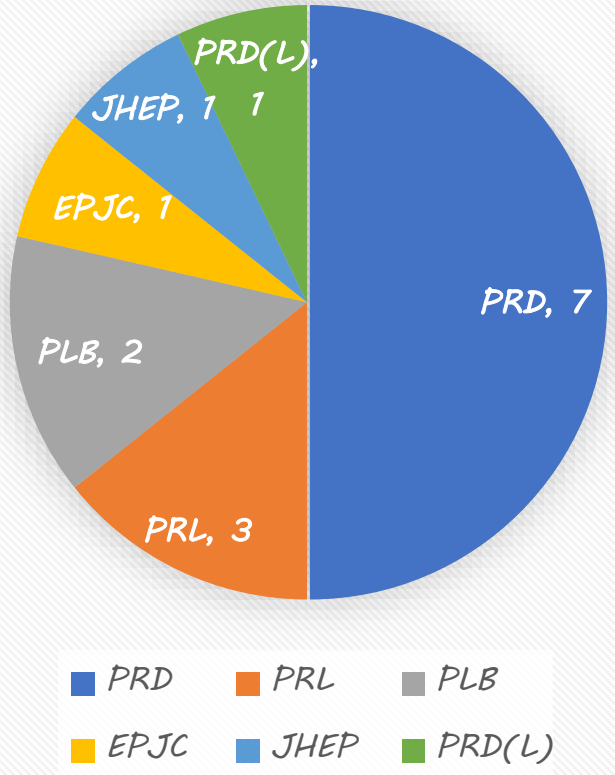
- **Inclusive decays of charm hadrons at BESIII:**

Published works:

	D^0/D^+	D_s^+	Λ_c^+
Single track		$Xe^+\nu_e$	$Xe^+\nu_e$
Multi track	$\pi^+\pi^+\pi^-X$	$\pi^+\pi^+\pi^-X$	
Long lived	K_S^0X		ΛX、K_S^0X
Short lived	ϕX	$\eta' X$	
Neutral			$\overline{\Lambda}_c^- \to \bar{n}X$

On-going analysis:

$\Lambda_c^+ \to K^-X$
$\Lambda_c^+ \to pX$
$\Lambda_c^+ \to \Sigma^{+/0}X$
$\Lambda_c^+ \to \Xi^-X$
$D^{+/0} \to Xe^+\nu_e$
$D^{+/0} \to X\mu^+\nu_\mu$
$D_s^+ \to Xe^+\nu_e$
$D_s^+ \to X\mu^+\nu_\mu$





Chapter 2

Inclusive semi-leptonic decay

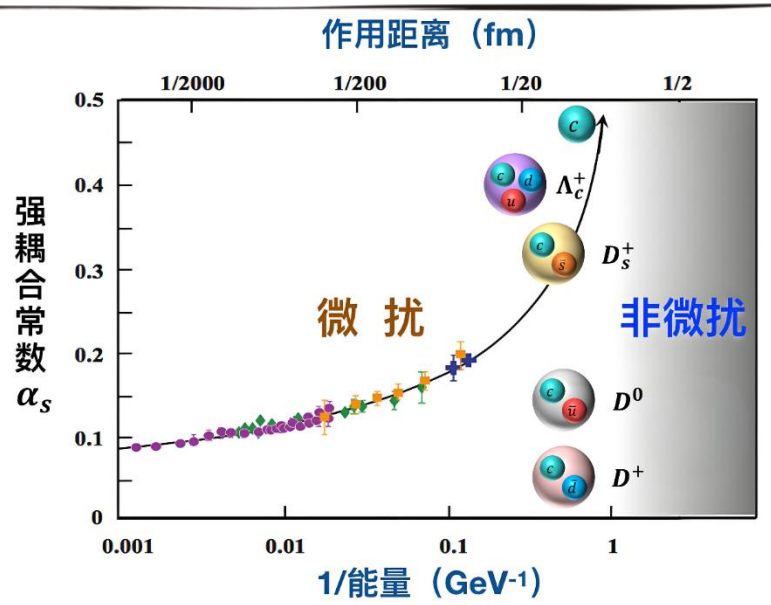
HQE: From Beauty to Charm

- Heavy Quark Expansion (HQE):

$$\Gamma_{\mathrm{SL}}(H_Q) = \Gamma_{\mathrm{parton}}\left[1 + \mathcal{O}\left(\frac{\Lambda^2_{\mathrm{QCD}}}{m_Q^2}\right) + \mathcal{O}\left(\frac{\Lambda^3_{\mathrm{QCD}}}{m_Q^3}\right) + \cdots\right]$$

Λ_{QCD} ~ 300MeV

For b quark: $\frac{\Lambda_{QCD}}{m_b} \sim \mathcal{O}^{-2}$, For c quark: $\frac{\Lambda_{QCD}}{m_c} \sim \mathcal{O}^{-1}$.

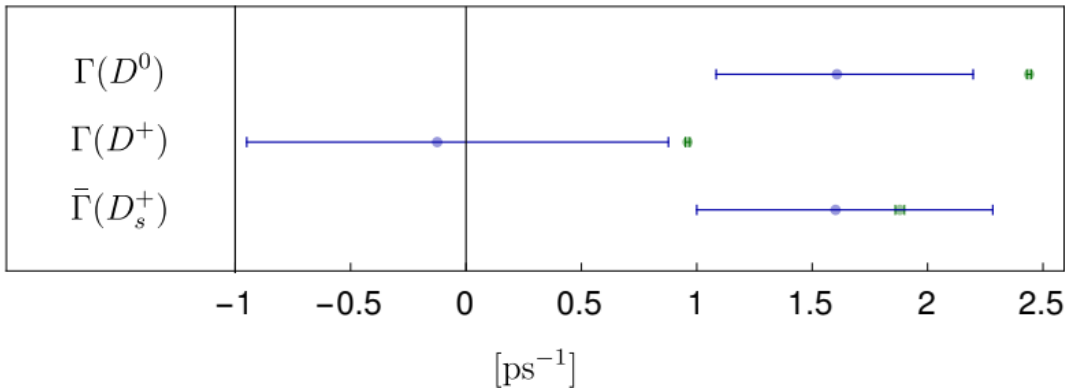


- The non-perturbative effects in the low-energy regime of QCD are one of the important frontier research topics in particle physics.

- In inclusive semi-leptonic B decays, HQE-based global fits consistently describe the measured rates and lepton-energy moments, however there are some abnormal in theoretical predictions in the sector of charm hadrons.

Puzzles in the lifetime of charm hadrons

- The predicted lifetimes of D mesons suffer from large uncertainty of input parameters:



JHEP 08 (2022) 241, A. Lenz et al.

Especially D^+ has negative theoretical prediction.

- The decay widths of D mesons can be expanded as:

non-perturbative parameters:

$$\Gamma_{SL} = \frac{G_F^2 m_c^5}{192\pi^3}|V_{cs}|^2\left[f_0(r) + \frac{\alpha_S}{\pi} f_1(r) + \frac{\alpha_S^2}{\pi^2} f_2(r) + \frac{\mu_\pi^2}{m_c^2} f_\pi(r) + \frac{\mu_G^2}{m_c^2} f_G(r) + \frac{\rho_{LS}^3}{m_c^3} f_{LS}(r) + \frac{\rho_D^3}{m_c^3} f_D(r) + \frac{32\pi^2}{m_c^3} B_{WA}\right]$$

α_S: Strong coupling constant

μ_π^2: Kinetic operator

μ_G^2: Chromomagnetic operator

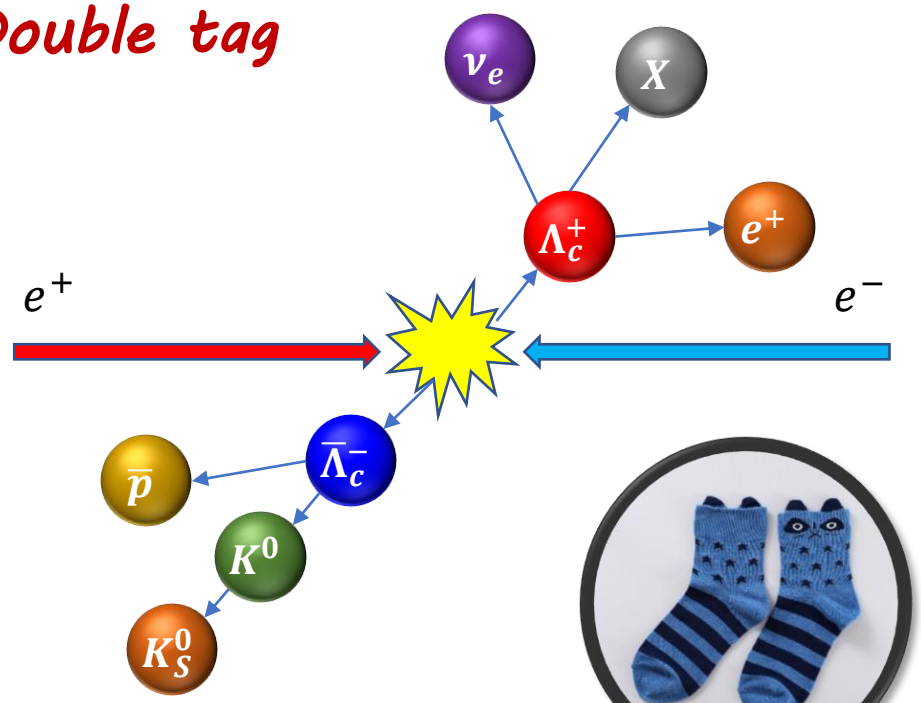
ρ_{LS}^3: Spin-orbital operator

ρ_D^3: Darwin operator

B_{WA}: Weak annihilation contribution

Methods for inclusive semi-leptonic decay

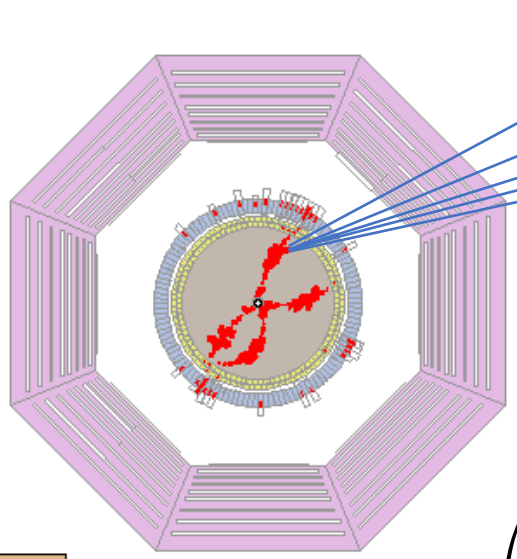
- Double tag

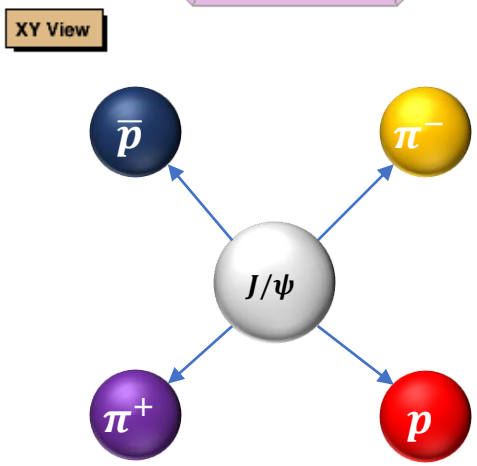


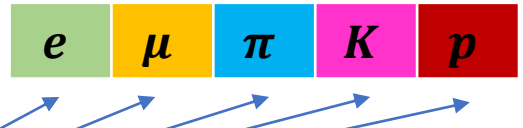
Advantages of double tag:

- Absolute BF, decay parameter, CPV;
- Less background than ST;
- Cancel out systematic uncertainties.

- Unfolding









$$\begin{pmatrix} N_e^{obs} \\ N_\mu^{obs} \\ N_\pi^{obs} \\ N_K^{obs} \\ N_p^{obs} \end{pmatrix} = \begin{pmatrix} P_{e\to e} & \cdots & P_{p\to e} \\ \vdots & \ddots & \vdots \\ P_{e\to p} & \cdots & P_{p\to p} \end{pmatrix} \cdot \begin{pmatrix} N_e^{true} \\ N_\mu^{true} \\ N_\pi^{true} \\ N_K^{true} \\ N_p^{true} \end{pmatrix}$$

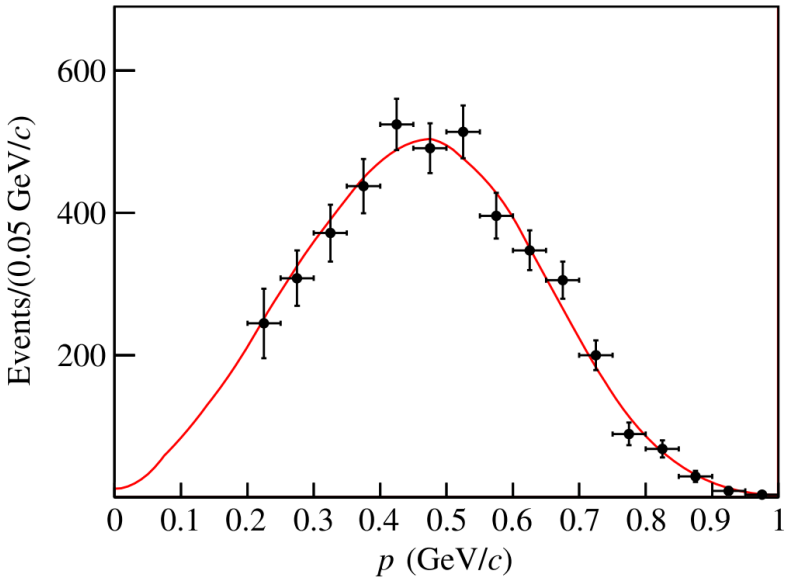
Control sample

Inclusive semi-leptonic decay at BESIII

- $\Lambda_c^+ \to Xe^+\nu_e$:

Phys. Rev. Lett. 121, 251801 (2018)

Phys. Rev. D. 107, 052005 (2023)



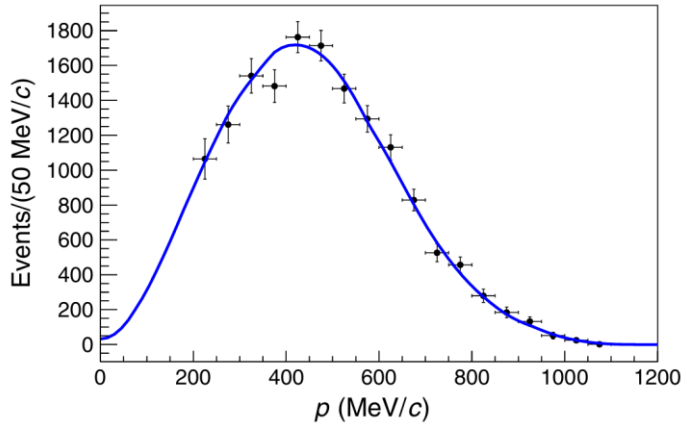
$$\mathcal{B}(\Lambda_c^+ \to Xe^+\nu_e) = (4.06 \pm 0.10_{\rm stat} \pm 0.09_{\rm syst})\%.$$

$$\frac{\Gamma_e(\Lambda_c^+)}{\overline{\Gamma}_e(D)} = 1.28 \pm 0.05$$

Effective-quark predicts ~ 1.67
Heavy-quark expansion ~ 1.2

- $D_s^+ \to Xe^+\nu_e$:

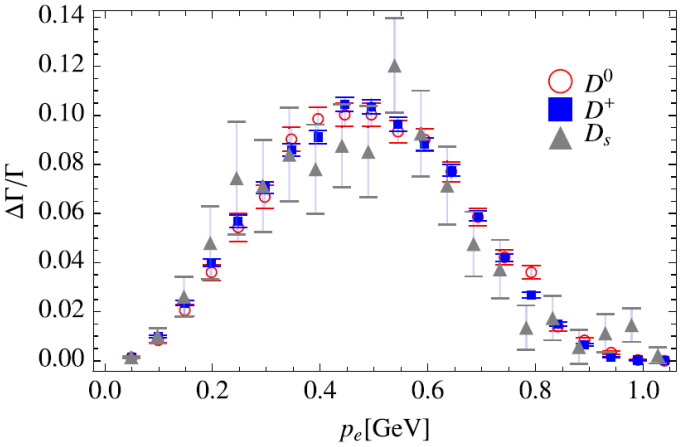
Phys. Rev. D. 104, 012003 (2021)



$$\mathcal{B}(D_s^+ \to Xe^+\nu_e) = (6.30 \pm 0.13_{\rm stat} \pm 0.09_{\rm syst} \pm 0.04_{\rm ext})\%,$$

$$\frac{\Gamma(D_s^+ \to Xe^+\nu_e)}{\Gamma(D^0 \to Xe^+\nu_e)} = 0.790 \pm 0.016_{\rm stat} \pm 0.011_{\rm syst} \pm 0.016_{\rm ext}.$$

Eur. Phys. J. C 85, 1011 (2025), Q. Qin et al.



Electron-energy moments inferred from CLEO and BESIII spectra constrain nonperturbative HQE parameters.

More inclusive semi-leptonic decays at BESIII are on-going.

$$D^+, D^0, D_s^+ \to Xe^+\nu_e \,/\, X\mu^+\nu_\mu, \qquad \Lambda_c^+ \to X\mu^+\nu_\mu$$



Chapter 3

Inclusive hadronic decay

Find unobserved decays

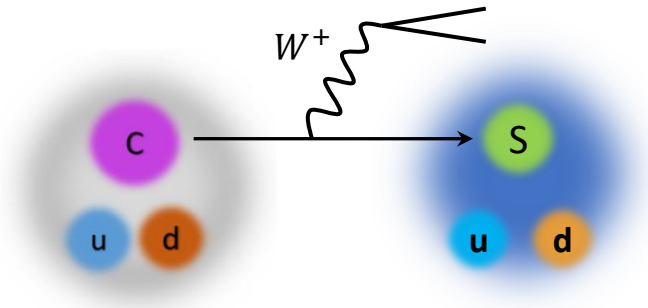
- Have we measured all the decay channels of a certain particle?

- $\Lambda_c^+ \to \Lambda X$: Phys. Rev. Lett. 121 062003

$$\mathcal{B}(\Lambda_c^+ \to \Lambda + X) = (38.2^{+2.8}_{-2.2} \pm 0.9)\%$$

- Sum of all exclusive: (33.6±1.1)%.

Remain ~ 4.6% containing Λ



- $\Lambda_c^+ \to K_S^0 X$: JHEP **06** (2025) 194

$$\mathcal{B}(\Lambda_c^+ \to \overline{K}^0/K^0 X) = (21.8 \pm 0.4 \pm 0.2)\%$$

- Sum of all exclusive: (15.8±0.6)%.

Remain ~ 6.0% containing K_S^0

Maybe we can search for decays containing Λ and K_S^0 simultaneously.

BESIII measured these channels for the first time.

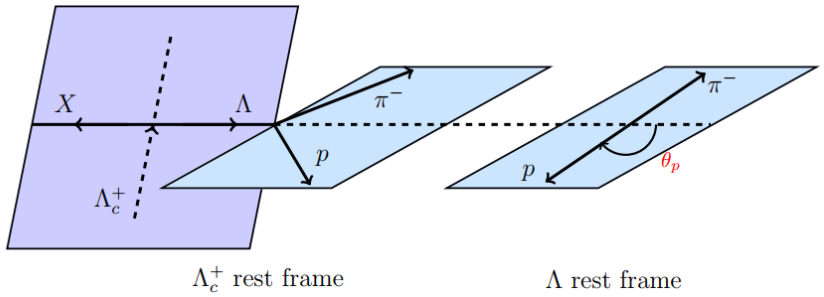
- $\Lambda_c^+ \to \Lambda K_S^0 h$、$\Sigma^0 K_S^0 h$、$\Xi^0 K_S^0 h$:

Phys. Rev. D **111**, 012014 | Phys. Rev. D **112**, 032006

	$\Lambda_c^+ \to \Lambda K_S^0 K^+$	$\Lambda_c^+ \to \Sigma^0 K_S^0 K^+$	$\Lambda_c^+ \to \Xi^0 K_S^0 \pi^+$
Geng *et al.* [5]	$(2.85 \pm 0.55) \times 10^{-3}$	$(2.50 \pm 0.50) \times 10^{-3}$	$(4.35 \pm 0.85) \times 10^{-2}$
Cen *et al.* [22]	$(2.90 \pm 0.50) \times 10^{-3}$	$(0.14 \pm 0.05) \times 10^{-3}$	$(2.20 \pm 0.40) \times 10^{-2}$
Geng *et al.* [23]	$(2.73 \pm 0.49) \times 10^{-3}$	$(1.27 \pm 0.48) \times 10^{-4}$	$(4.85 \pm 1.65) \times 10^{-3}$
Statistical isospin model [24]	...	...	$(3.10 \pm 0.30) \times 10^{-3}$
PDG value [20]	$(2.80 \pm 0.55) \times 10^{-3}$	...	...
This work	$(3.12 \pm 0.46 \pm 0.15) \times 10^{-3}$	$(0.80^{+0.28}_{-0.24} \pm 0.16) \times 10^{-3}$	$(3.70 \pm 0.60 \pm 0.21) \times 10^{-3}$

Search for CP violation

- Sakharov conditions:
- Baryon number violation
- C and CP violation
- Departure from thermal equilibrium

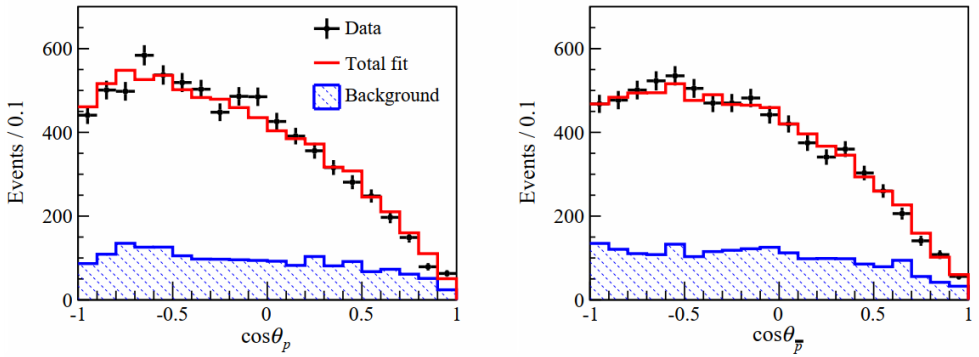


Phys. Lett. B 849 (2024) 138460 J.P. Wang, F.S. Yu, et al.

- CPV in inclusive baryonic decay $\Lambda_c^+ \to \Lambda X$:

$$\frac{d\Gamma}{d\cos\theta} \propto 1 + \mathcal{P}\alpha_\Lambda \cos\theta \quad \Rightarrow \quad \mathcal{P} = \langle \mathcal{P}(q^2) \rangle \quad \Rightarrow \quad A_{CP}^{\alpha}(\Lambda_c \to \Lambda X) = \frac{\mathcal{P}\alpha - \bar{\mathcal{P}}\bar{\alpha}}{\mathcal{P}\alpha + \bar{\mathcal{P}}\bar{\alpha}}$$

- Inclusive asymmetry will indicate net, integrated difference in decay dynamics between B and $\bar{B}$.



Phys. Rev. Lett. 137 (2026) 131902

$$\begin{cases} \mathcal{B}(\Lambda_c^+ \to \Lambda X) = (38.07 \pm 0.38 \pm 0.49)\% \\ \mathcal{P}_\Lambda = -0.393 \pm 0.055 \pm 0.020 \\ \mathcal{P}_{\bar{\Lambda}} = 0.288 \pm 0.056 \pm 0.017 \\ \mathcal{A}_{CP}^{dir} = (1.5 \pm 1.0 \pm 1.0)\% \\ \mathcal{A}_{CP}^{pol} = 0.15 \pm 0.12 \pm 0.03 \end{cases}$$

First measurement of the polarization and search for its induced CP asymmetry in inclusive decay.

Test isospin symmetry

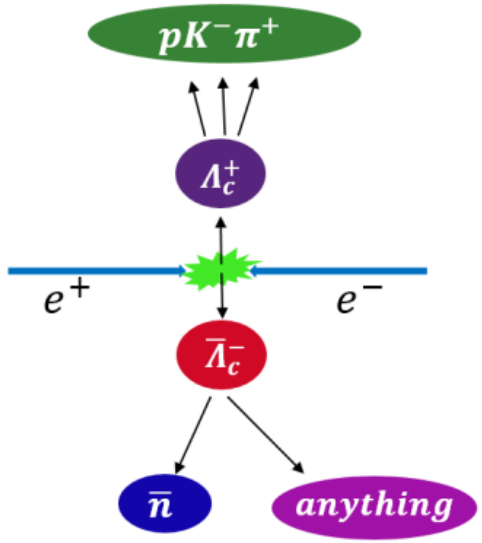
- $\bar{\Lambda}_c^- \to \bar{n}X$:

Phys. Rev. D 108 L031101

L.Q. Zhang, et al. BESIII 2023

Γ_{77}	p anything	$(50 \pm 16)\%$
Γ_{78}	n anything	$(50 \pm 16)\%$

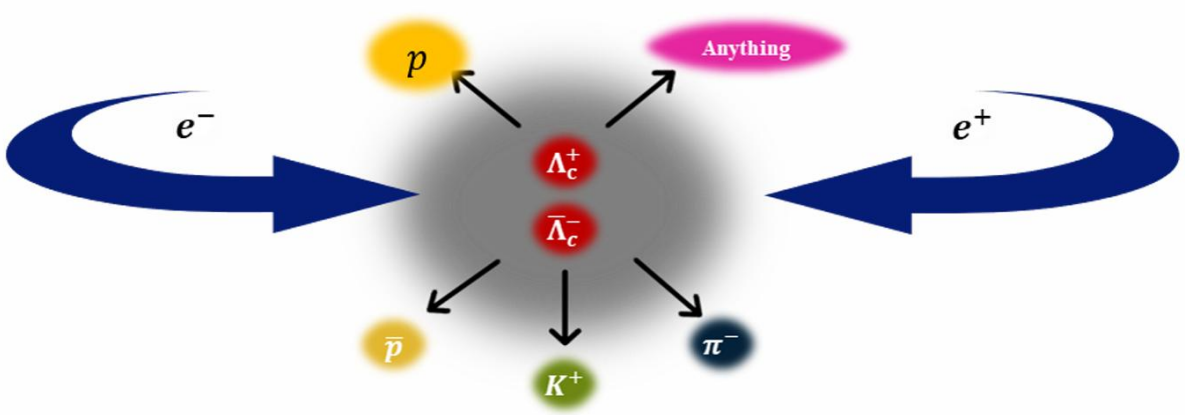
from PDG



The sum of exclusive decays of $\Lambda_c^+ \to pX$ and $\Lambda_c^+ \to nX$ are 44.5%、25.4%. Precise determination of inclusive decay may help search for undiscovered exclusive decays and test isospin symmetry.

Results: $\mathcal{B}(\bar{\Lambda}_c^- \to \bar{n} + X) = (32.4 \pm 0.7 \pm 1.5)\%$ Sum of exclusive: (25.4 ± 0.8) %

- $\Lambda_c^+ \to pX$:



Summary & Prospect

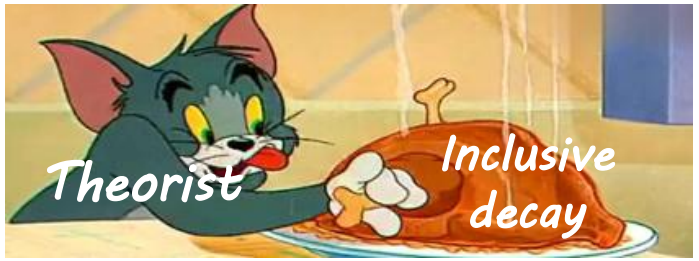
- BESIII is an ideal platform to study inclusive decay and has obtained a series of achievement on inclusive decays, mature analytical techniques are developed.

- Inclusive decays of charmed hadrons are widely studied, published results:
  - $\Lambda_c^+ \to \Lambda X$、 $\Lambda_c^+ \to K_S^0 X$、 $\bar{\Lambda}_c^- \to \bar{n} X$、 $\Lambda_c^+ \to X e^+ \nu_e$、 $D_s^+ \to X e^+ \nu_e$

- Some on-going analyses of inclusive decay at BESIII:
  - $\Lambda_c^+ \to p X$、 $\Lambda_c^+ \to \Sigma^+ X$、 $\Lambda_c^+ \to \Sigma^0 X$、 $D^{0/+} \to X e^+ \nu_e$、 $D^{0/+} \to X \mu^+ \nu_\mu$

- A lot inclusive decays of charmed meson are performed mainly on BES2 and CLEO, waiting for update:
  - $D^{0/+} \to K^{\pm} X$、 $D^{0/+} \to K_S^0 X$、 $D^{0/+} \to K^{*0/-} X$、 $D^{0/+} \to \eta^{(\prime)} X$、 $D^{0/+} \to \phi X$ …
  - $D_s^+ \to K^{\pm} X$、 $D_s^+ \to K_S^0 X$、 $D_s^+ \to K^{*0/-} X$、 $D_s^+ \to \eta^{(\prime)} X$、 $D_s^+ \to \phi X$ …

- Eager for theoretical research and cooperation on inclusive decay!





谢谢！敬请批评指正！