Rare Charm Meson Decays at BESIII

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2024年BESIII粲强子物理研讨会，5月10-13日，郑州

Outline

- Introduction
- Results at BESIII
  - $D^{\pm} \to n(\bar{n})e^{\pm}$ (PRD 106, 112009 (2022))
  - $D_s^{+} \to h^{+}(h^{0})e^{+}e^{-}$ (arXiv:2404.05973)
- Prospects
- Summary

Introduction

- Rare charm meson decays provide a unique environment for testing the Standard Model and searching for New Physics.

- BESIII has collected a large charm meson sample, and has a great potential to search for rare and forbidden D decays due to the clean environment and low charge confusion rates.

- Interesting topics: radiative decays, FCNC, LNV, LFV, BNV …

Results at BESIII

Previous results

- $D \to h\,(h^{(\prime)})e^+e^-$ (PRD 97, 072015 (2018))
- $D \to K\pi e^+e^+$ (PRD 99, 112002 (2019))
- $D^+ \to \bar{\Lambda}(\bar{\Sigma}^0)e^+, D^+ \to \Lambda(\Sigma^0)\,e^+$ (PRD 101, 031102 (2020))
- $D^0 \to pe^-/\bar{p}e^+$ (PRD 105, 032006 (2022))
- $D^0 \to \pi^0\nu\bar{\nu}$ (PRD 105, L071102 (2022))

Results at BESIII

Highlights of recent results

- B&LNV $D^{\pm} \to n(\bar{n})e^{\pm}$ (PRD 106, 112009 (2022))
- FCNC $D_s^{+} \to h^{+}(h^{0})e^{+}e^{-}$ (arXiv:2404.05973)

$D^{\pm} \to n(\bar{n})e^{\pm}$

PRD 106, 112009 (2022)

- In most grand unified theories (GUTs) and some SM extension models, baryon-number and lepton-number violation (LNV) processes with the difference of baryon and lepton conserved ($\Delta|B-L|=0$) are allowed under dimension-six operators.
- Another kind of B&LNV processes with $\Delta|B-L|=2$ is possible under dimension-seven operators.

  PRD 8, 1240 (1973);
  PRL 32, 438 (1974);
  PRD 20, 776(1979);
  PLB 91, 222 (1980);
  PLB 314, 336(1993).
- The decay amplitudes of these two kinds of BNV processes are expected to be of comparable strength. PLB 88, 311 (1979)

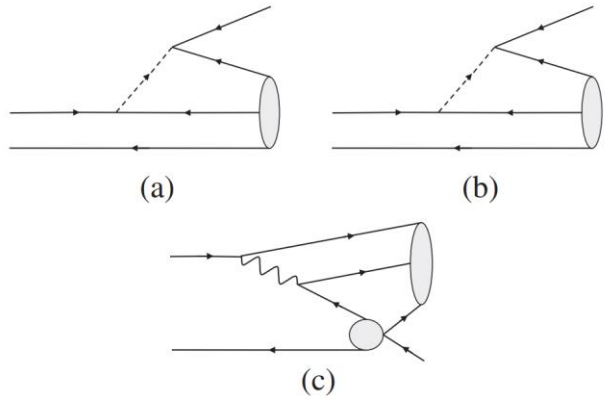


FIG. 1. Feynman diagrams for $D^+ \to \bar{n}e^+$ with heavy gauge bosons X (a) and Y (b), and $D^+ \to ne^+$ with elementary scalar fields ϕ (c).

$D^{\pm} \to n(\bar{n})e^{\pm}$

PRD 106, 112009 (2022)

- Data: 2.93 fb^{-1} @3.773 GeV

- Double tag analysis; Blind analysis

$$\mathcal{B}_{\text{sig}} = N_{\text{DT}}/(N_{\text{ST}}^{\text{tot}} \cdot \epsilon_{\text{sig}})$$

- Two variables are used to identify the ST candidates:

$$M_{\text{BC}} = \sqrt{E_{\text{beam}}^2 - |\vec{p}_D|^2},$$
$$\Delta E = E_D - E_{\text{beam}},$$

- Multivariate Data Analysis (MVA) is performed to further suppress background

TABLE I. Summary of ST yields N_{ST}^i, ST efficiencies $\epsilon_{\text{ST}}^i(\%)$, and DT efficiencies $\epsilon_{\text{DT}}^{i,c1}$ and $\epsilon_{\text{DT}}^{i,c2}(\%)$, for the different ST decay modes, which are used to calculate $N_{\text{ST}}^{\text{tot}}$ and ϵ_{sig} in Eq. (1). $\epsilon_{\text{DT}}^{i,c1}$ and $\epsilon_{\text{DT}}^{i,c2}$ are DT efficiencies for signal channels with $\Delta|B-L|=0$ and $\Delta|B-L|=2$, respectively.

ST modes	$N_{\text{ST}}^i(\times 10^3)$	ϵ_{ST}^i	$\epsilon_{\text{DT}}^{i,c1}$	$\epsilon_{\text{DT}}^{i,c2}$
$D^+ \to K^-\pi^+\pi^+$	390.2 ± 1.1	50.22 ± 0.03	9.79	9.26
$D^+ \to K^-\pi^+\pi^+\pi^0$	124.0 ± 0.6	26.40 ± 0.05	5.51	5.21
$D^+ \to K_S^0\pi^+$	45.9 ± 0.2	50.58 ± 0.10	9.69	9.17
$D^+ \to K_S^0\pi^+\pi^0$	106.7 ± 0.6	27.07 ± 0.06	5.66	5.36
$D^+ \to K_S^0\pi^+\pi^+\pi^-$	56.9 ± 0.4	28.16 ± 0.08	5.64	5.34
$D^+ \to K^+K^-\pi^+$	34.6 ± 0.3	41.13 ± 0.15	7.88	7.46
$D^- \to K^+\pi^-\pi^-$	392.4 ± 0.7	51.19 ± 0.03	9.21	9.72
$D^- \to K^+\pi^-\pi^-\pi^0$	127.7 ± 1.0	26.86 ± 0.06	5.19	5.47
$D^- \to K_S^0\pi^-$	45.5 ± 0.2	50.64 ± 0.09	9.12	9.62
$D^- \to K_S^0\pi^-\pi^0$	107.6 ± 0.6	27.21 ± 0.05	5.33	5.63
$D^- \to K_S^0\pi^-\pi^-\pi^+$	56.2 ± 0.4	27.87 ± 0.07	5.31	5.60
$D^- \to K^+K^-\pi^-$	34.6 ± 0.3	40.40 ± 0.12	7.42	7.83

$D^{\pm} \to n(\bar{n})e^{\pm}$

PRD 106, 112009 (2022)

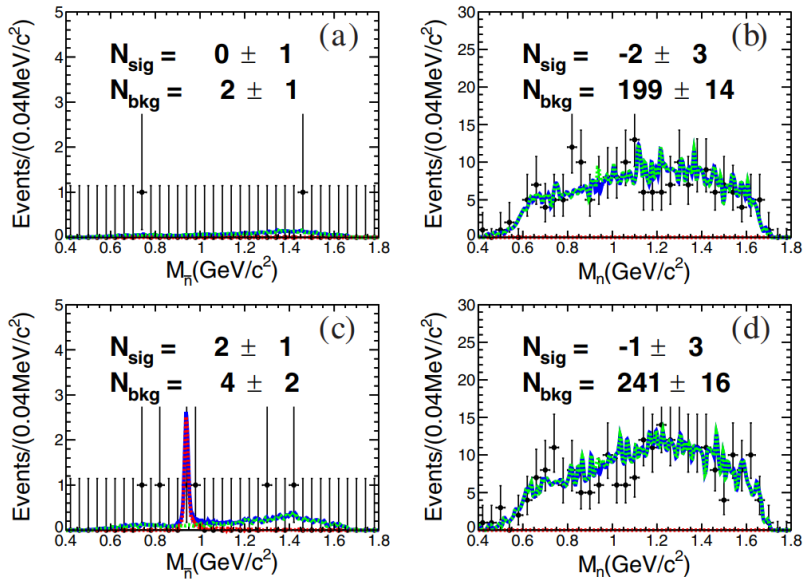


FIG. 4. Fit for $M_{n/\bar{n}}$ distributions for processes (a) $D^+ \to \bar{n}e^+$, (b) $D^- \to ne^-$, (c) $D^- \to \bar{n}e^-$, and (d) $D^+ \to ne^+$. The black dots with error bar are data. The red dotted, green dotted and blue solid lines are signal, background, and the sum of signal and background, respectively.

signal and background are modeled by the MC simulated shapes obtained from signal and inclusive MC samples, respectively

- Fit to the mass distributions of (anti)neutron $M_{n/\bar{n}}$ to extract signal
- Scanning likelihood value for different number of signal events.
- The most conservative ULs @ 90% C.L.:

$$\mathcal{B}_{D^+ \to \bar{n}e^+} < 1.43 \times 10^{-5}$$

$$\mathcal{B}_{D^+ \to ne^+} < 2.91 \times 10^{-5}$$

first search

possible to improved by a factor of three with 20 fb^{-1} data

$D_s^+ \to h^+(h^0)e^+e^-$

arXiv:2404.05973

- Dominated by long-distance (LD) contributions, expect the BFs of $D_s^+ \to Ve^+e^-$ to reach 10^{-5};
- Short-distance (SD) contributions proceed via the $c \to ul^+l^-$ flavor-changing neutral-current (FCNC) transition are highly suppressed by the GIM mechanism, leading to naive SD-only BFs as low as 10^{-9}.

PRL 93, 074001 (2016);
EPJC 75, 567 (2015);
JHEP 04, 135(2013);
PRD 90, 014035 (2014);
JHEP 08, 091(2017)

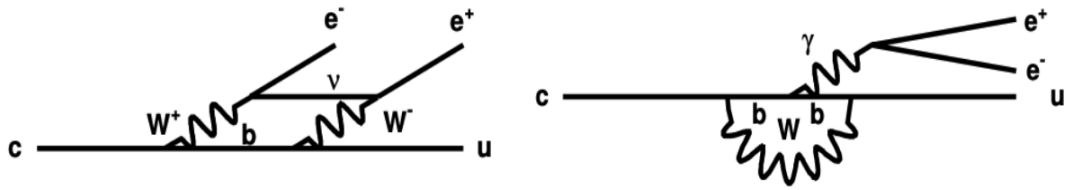


Figure 1: The SD contributions in $D_{(s)} \to h(h')l^+l^-$ processes.

- Sensitive to new physics, which may significantly enhance the BFs through the presence of new particles and interactions.
- Compared with lepton universality test in the beauty-quark FCNC decays, results in $c \to ul^+l^-$ deacys are largely unexplored due to limited experimental results on di-electron modes.

$D_s^+ \to h^+(h^0)e^+e^-$

arXiv:2404.05973

- Data: 7.33 fb^{-1} @4.128−4.226 GeV
- Single tag analysis

  $e^+e^- \to D_s^+ D_s^{*-}$

  $D_s^+ \to \pi^+\phi$ with $\phi \to e^+e^-$; $D_s^+ \to \rho^+\phi$ with $\rho^+ \to \pi^+\,\pi^0$ and $\phi \to e^+e^-$;

  $D_s^+ \to \pi^+\pi^0/K^+\pi^0/K_s^0\pi^+e^+e^-$

  $D_s^- \to$ anything

$$\mathcal{B}(D_s^+ \to h^+(h^0)e^+e^-) = \frac{N_{\rm sig}}{2 \cdot N_{D_s^{*\pm}D_s^{\mp}} \cdot \epsilon \cdot \mathcal{B}_{\rm inter}}$$

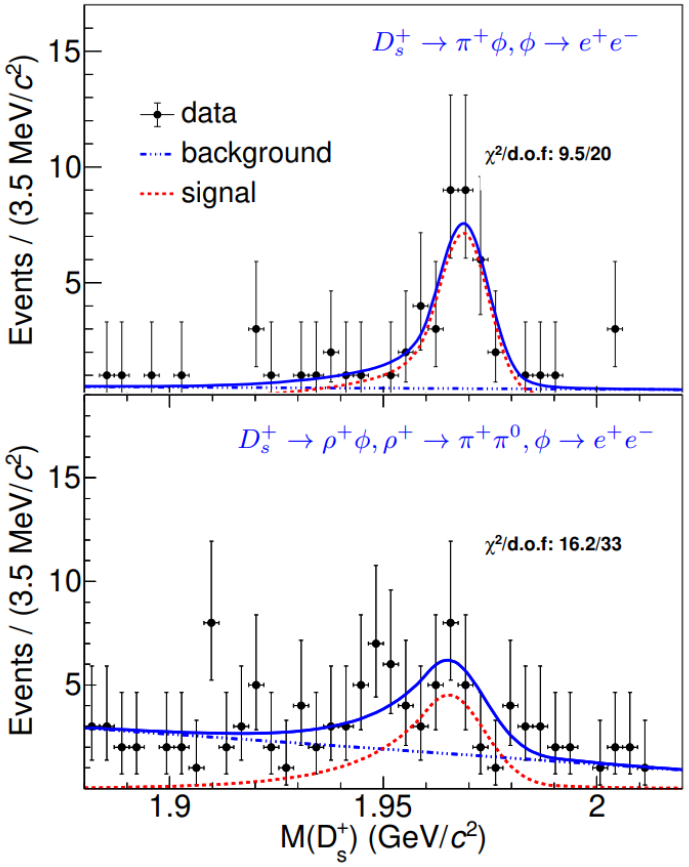
- $N_{D_s^{*+}D_s^-} = (64.72 \pm 0.28) \times 10^5$ is the total number of $D_s^{*+}D_s^-$ pair, measured by BESIII recently (arXiv:2403.19256)

- Two variables are used to further suppress backgrounds and identify the signal candidates. Signal candidates are required to lie within the signal windows in the two-dimensional plane of M_{rec} versus ΔM.

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

$D_s^+ \to h^+(h^0)e^+e^-$

arXiv:2404.05973



signal modeled by a double-sided Crystal Ball function plus a bifurcated Gaussian function, background modeled by a first-order Chebychev polynomial function

- $M(e^+e^-) \in [0.98,1.04]$ GeV/c^2
- $M(\pi^+\pi^0) \in [0.60,0.95]$ GeV/c^2
- Unbinned maximum likelihood fits to the $M(D_s^+)$ distributions

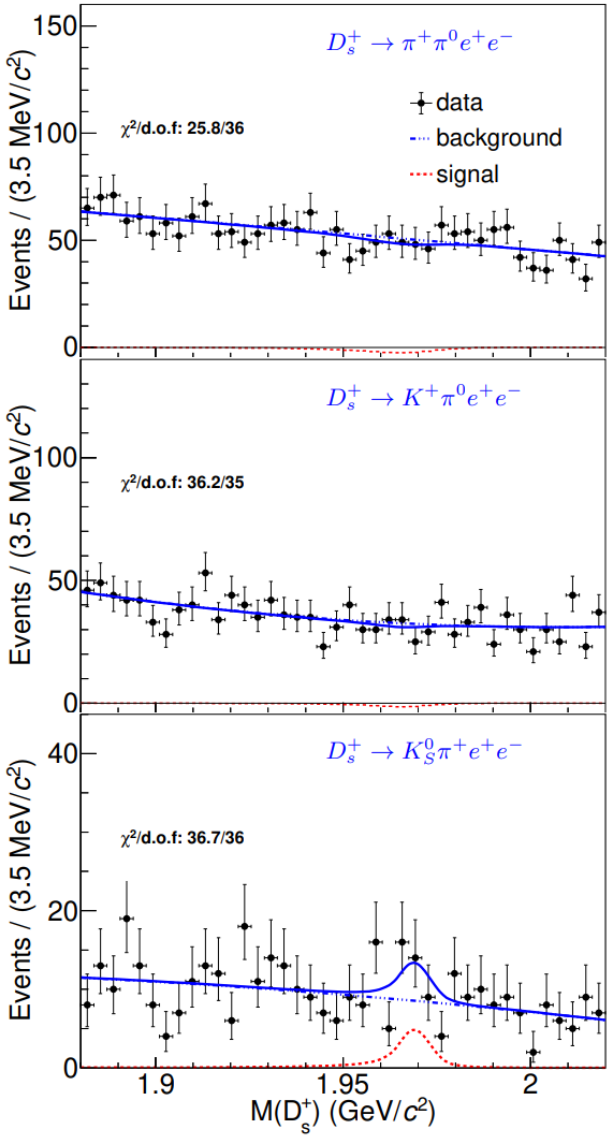
Decay	$N_{\rm sig}$	ϵ (%)	$\mathcal{B}$ ($\times 10^{-5}$)
$D_s^+ \to \pi^+\phi, \phi \to e^+e^-$	$38.2^{+7.8}_{-6.8}$	25.1	$1.17^{+0.23}_{-0.21} \pm 0.03$
$D_s^+ \to \rho^+\phi, \phi \to e^+e^-$	$37.8^{+10.3}_{-9.6}$	12.1	$2.44^{+0.67}_{-0.62} \pm 0.16$

7.8σ for $D_s^+ \to \pi^+\phi, \phi \to e^+e^-$ — improved by a factor of three

4.4σ for $D_s^+ \to \rho^+\phi, \phi \to e^+e^-$ — first evidence

$D_s^+ \to h^+(h^0)e^+e^-$

arXiv:2404.05973



- Exclude events with $M(e^+e^-) \in [0.96,1.05]$ GeV/c^2 for the non-resonant $D_s^+ \to \pi^+\pi^0 e^+e^-$ decay
- Scanning likelihood value for different number of signal events.
- ULs @ 90% C.L.:

Decay	$N_{\rm sig}$	ϵ (%)	$\mathcal{B}$ ($\times 10^{-5}$)
$D_s^+ \to \pi^+\pi^0 e^+e^-$	...	7.4	< 7.0
$D_s^+ \to K^+\pi^0 e^+e^-$	...	5.3	< 7.1
$D_s^+ \to K_S^0\pi^+ e^+e^-$	...	6.7	< 8.1

signal modeled by a double-sided Crystal Ball function plus a bifurcated Gaussian function, background modeled by a second-order Chebychev polynomial function

Results at LHCb, Belle

- LHCb
  - ➢ $D^0 \to \mu^+\mu^-$ (PRL 131, 041804 (2023))

    FCNC process, expected BF of the order of 10^{-18}.

    Data: Run 1 + Run 2, 9 fb^{-1} @7, 8, 13 TeV

$$\mathcal{B}(D^0 \to \mu^+\mu^-) < 3.1(3.5) \times 10^{-9} \text{ at } 90(95)\%\text{C.L.}$$

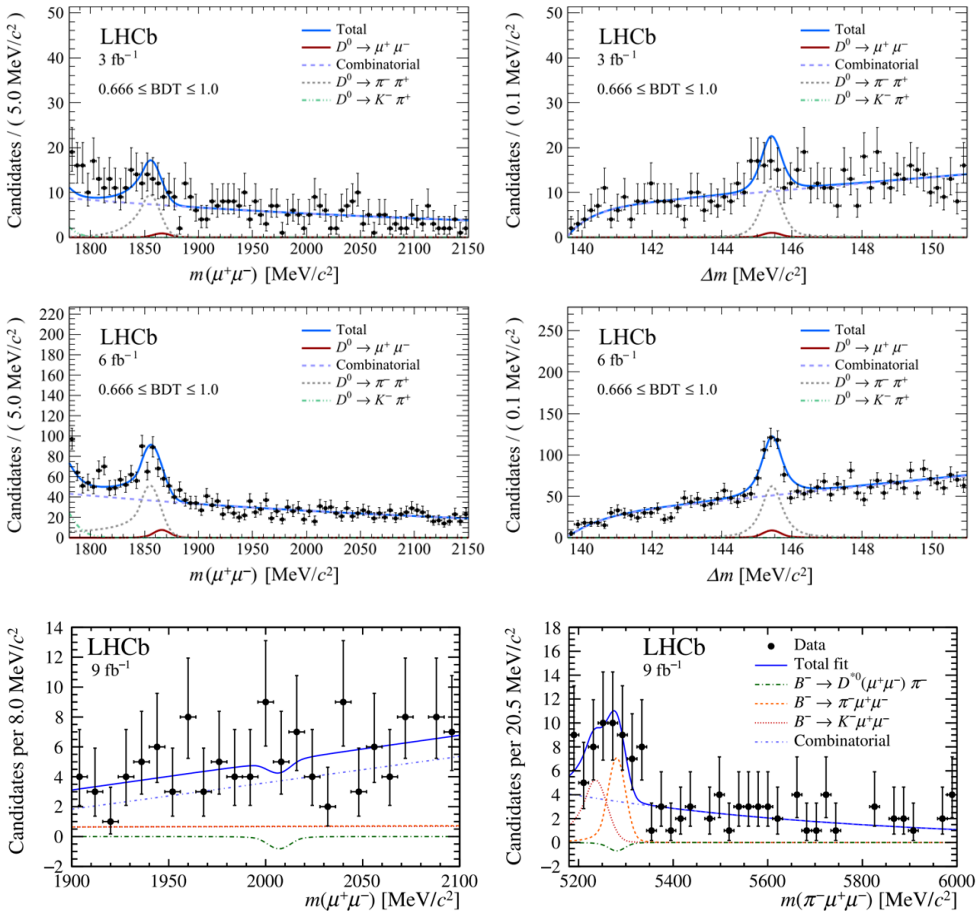
improved by more than a factor of 2 with respect to the previous LHCb result

  - ➢ $D^*(2007)^0 \to \mu^+\mu^-$ in $B^- \to \pi^-\mu^+\mu^-$ decays (EPJC (2023) 83: 666)

$$\mathcal{B}(D^{*0} \to \mu^+\mu^-) < 2.6\,(3.4) \times 10^{-8} \text{ at } 90\,(95)\%\text{ CL}.$$

first limit

Talk "Synergy between LHCb and BESIII charm program" by Wenbin Qian
and "Charm physics at Belle (II)" by Yang Li



Results at LHCb, Belle

- Belle
  - ➢B&LNV $D \to pl$ (PRD 109, L031101 (2024))

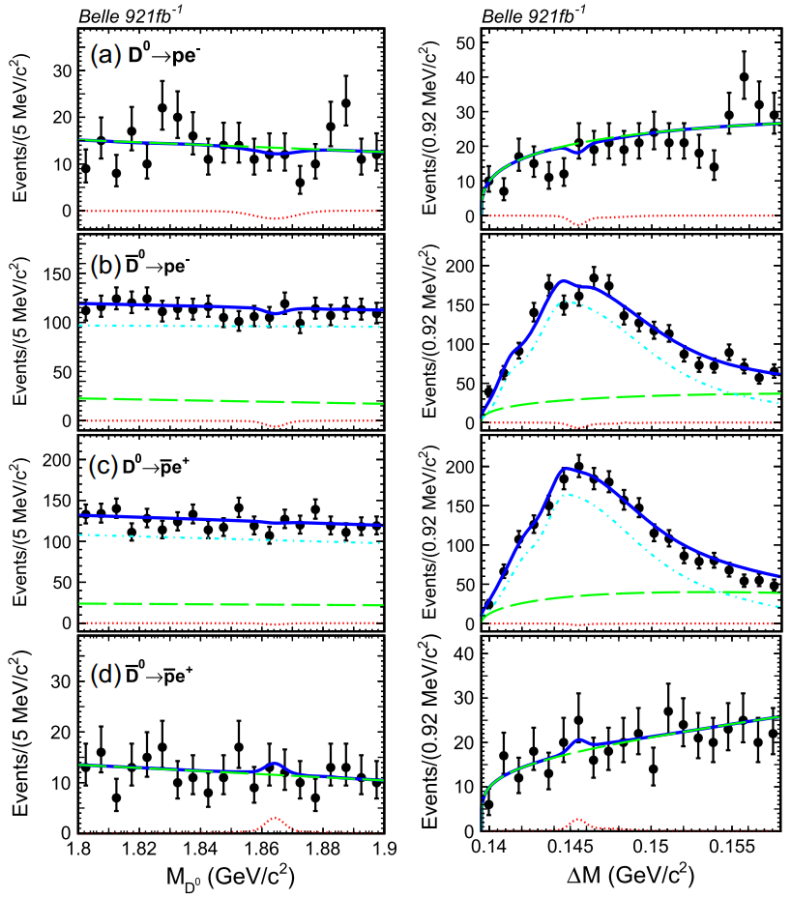
    B&LNV process with $\Delta|B-L|=0$, predicted BF of the order of 10^{-39}.

    Search for $D \to pl$, where D is either a D^0 or $\overline{D}^0$ and l is a muon or an electron.

    Data: 921 fb^{-1}

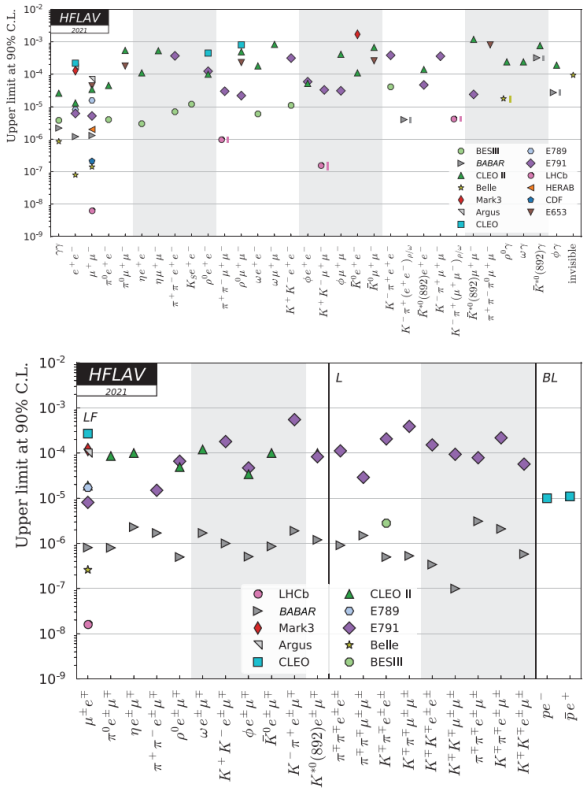
ULs at 90% C.L. in the range of $(5-8)\times 10^{-7}$

most stringent limit to date;
first measurement for the muon channels

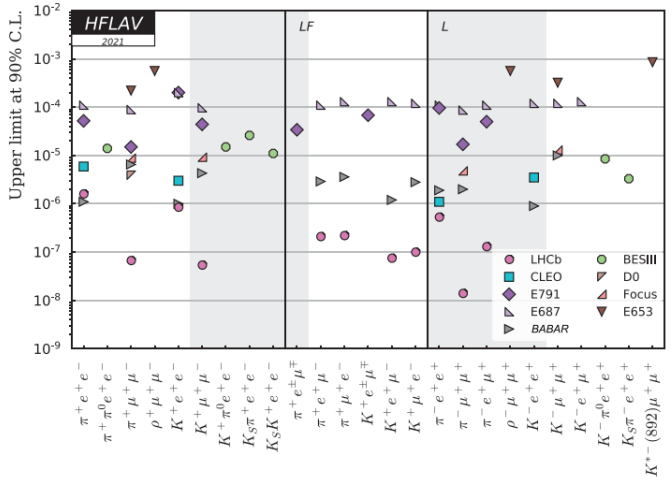


Prospects

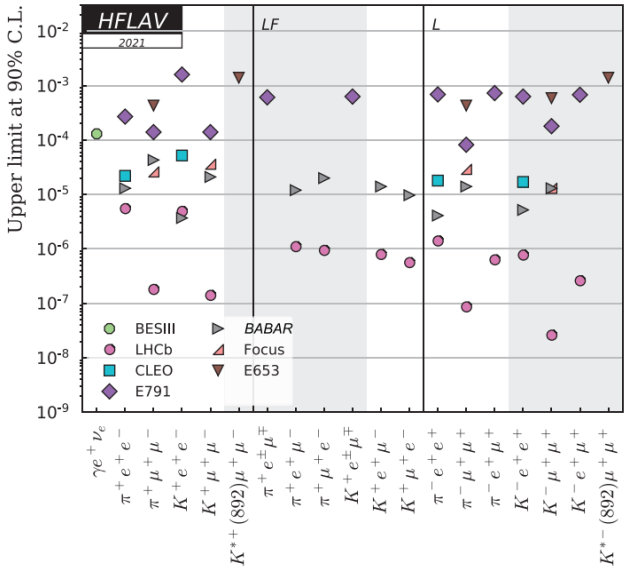
Averages of b-hadron, c-hadron, and τ-lepton properties as of 2021. (HFLAV Collaboration). Phys. Rev. D. 107, 052008 (2023)



D^0



D^+

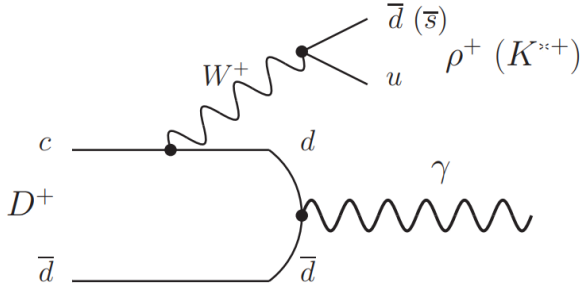


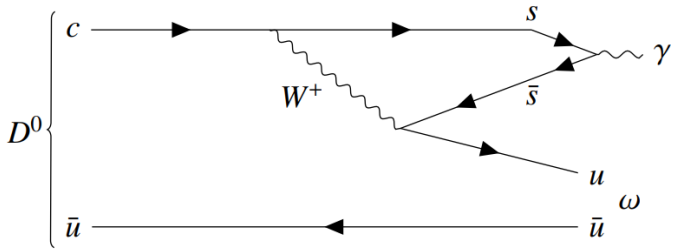
D_s

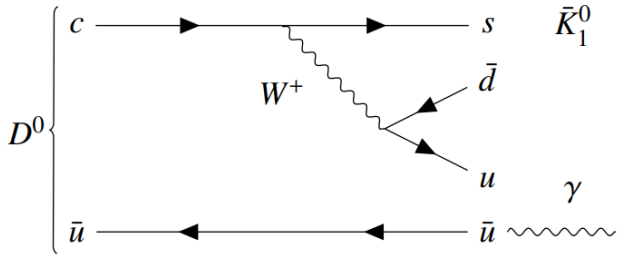
- Many modes haven't been searched for, e.g. four-body LNV decays of D_s, four-body LFV decays of D^+ and D_s, etc.

Prospects

- Works about rare D decays ongoing:
  - Absolute measurements of the branching fractions of $D^0 \to \gamma \bar{K}^{*0}$ and $D^0 \to \gamma\phi$ [BAM-592]
  - Search for the radiative decays $D^+ \to \gamma\rho^+$ and $D^+ \to \gamma K^{*+}$ [BAM-667]
  - Search for the radiative decay $D^0 \to \gamma\omega$ [BAM-708]
  - Search for the radiative decay $D_s^+ \to \gamma\rho^+$ [BAM-762]
  - Search for the radiative decays $D^0 \to \gamma \bar{K}_1^0(1270)$ and $D^+ \to \gamma K_1^+(1270)$ [BAM-837]
  - Search for the radiative decays $D_s^+ \to \gamma K^*(892)^+$ [early stage]
  - Search for the radiative decays $D_s^+ \to \gamma K_1^+(1270)$ [early stage]

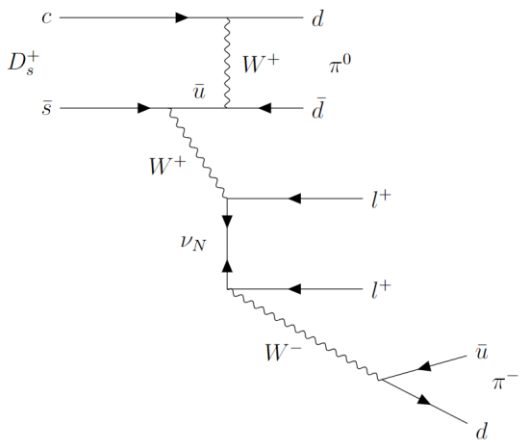


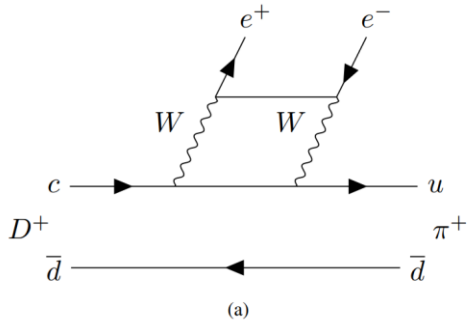


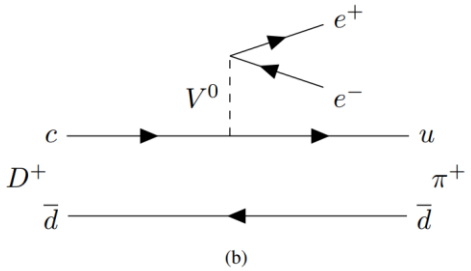


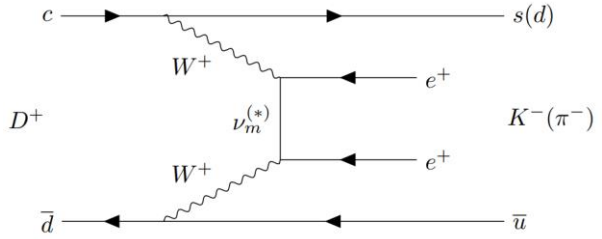
Prospects

- Works about rare D decays ongoing:
  - Search for Lepton Number Violating Decays of $D_s^+ \to hh'e^+e^+$ [BAM-786]
  - Search for FCNC process $D^+ \to h^+e^+e^-$ and LNV process $D^+ \to h^+e^+e^+$ [memo just ready]
  - Search for four-body LFV D_s^+ decays [early stage]
  - Search for the decay $D^+ \to \pi^+$ + invisible [early stage]









Prospects

BESIII Collaboration, Future physics programme of BESIII, Chin. Phys. C 44 (2020), 040001

Table 6.2. The latest experimental upper limits on the branching fractions (in units of 10^{-6}) of the rare D and D_s decays into $h(h')e^+e^-$. The expected BESIII sensitivities with the expected final charm data set listed in Sec. 7 are also shown in the last column.

Decay	Upper limit	Experiment	Year	Ref.	BESIII Expected
$D^0 \to \pi^0 e^+ e^-$	0.4	BESIII	2018	[35]	0.1
$D^0 \to \eta e^+ e^-$	0.3	BESIII	2018	[35]	0.1
$D^0 \to \omega e^+ e^-$	0.6	BESIII	2018	[35]	0.2
$D^0 \to K_S^0 e^+ e^-$	1.2	BESIII	2018	[35]	0.5
$D^0 \to \rho e^+ e^-$	124.0	E791	2001	[36]	0.5
$D^0 \to \phi e^+ e^-$	59.0	E791	2001	[36]	0.5
$D^0 \to \bar{K}^{*0} e^+ e^-$	47.0	E791	2001	[36]	0.5
$D^0 \to \pi^+ \pi^- e^+ e^-$	0.7	BESIII	2018	[35]	0.3
$D^0 \to K^+ K^- e^+ e^-$	1.1	BESIII	2018	[35]	0.4
$D^0 \to K^- \pi^+ e^+ e^-$	4.1	BESIII	2018	[35]	1.6
$D^+ \to \pi^+ e^+ e^-$	1.1	BaBar	2011	[37]	0.12
$D^+ \to K^+ e^+ e^-$	1.0	BaBar	2011	[37]	0.46
$D^+ \to \pi^+ \pi^0 e^+ e^-$	1.4	BESIII	2018	[35]	0.5
$D^+ \to \pi^+ K_S^0 e^+ e^-$	2.6	BESIII	2018	[35]	1.0
$D^+ \to K_S^0 K^+ e^+ e^-$	1.1	BESIII	2018	[35]	0.4
$D^+ \to K^+ \pi^0 e^+ e^-$	1.5	BESIII	2018	[35]	0.6
$D_s^+ \to \pi^+ e^+ e^-$	13.0	BaBar	2011	[37]	70.0
$D_s^+ \to K^+ e^+ e^-$	3.7	BaBar	2011	[37]	1.7

- For LNV processes of D mesons: could improve the best upper limit to 4.6×10^{-7} and 2.3×10^{-7} for $D^+ \to \pi^- e^+ e^+$ and $D^+ \to K^- e^+ e^+$.

Summary

- In recent years, BESIII have searched for various rare charm meson decays.

  Upper limits of many processes have been determined, providing stringent restrictions on the parameters of the future theoretical development.

- With 20 fb^{-1} of $\psi(3770)$ data samples, more and better results for rare charm-meson decays are expected.