粲强子辐射、稀有衰变的实验测量

刘雪吟
武汉大学

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Outline

① Rare charm hadron decays at BESIII

② Latest results at BESIII

- Search for weak radiative decays
- Search for LNV decays
- Search for dark photon

③ Recent highlight from LHCb

④ Prospect & Summary

Rare charm hadron decays at BESIII

Weak radiative decays

Symmetry

- BNV, LNV, LFV processes, ...

Very rare

- FCNC processes, other rare decays, ...

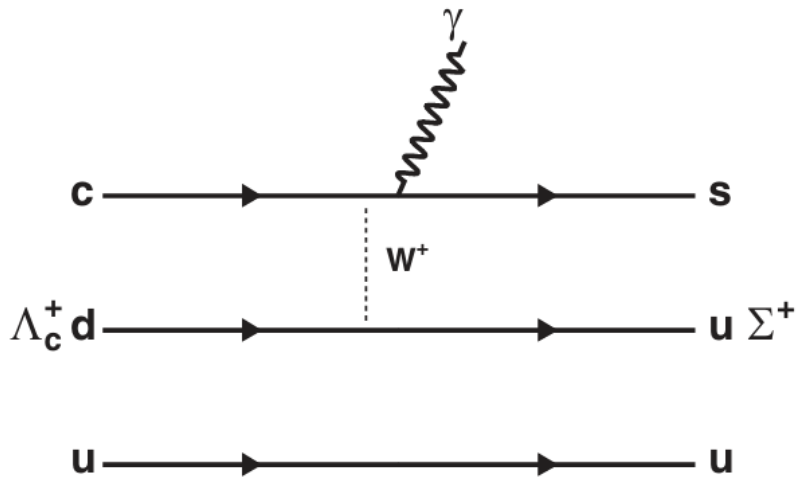
Exotic

- Dark photons, light Higgs, Z', invisible signatures, exotic resonances, ...

Search for the weak radiative decay $\Lambda_c^+ \to \Sigma^+\gamma$ at BESIII

PRD 107, 052002 (2023)

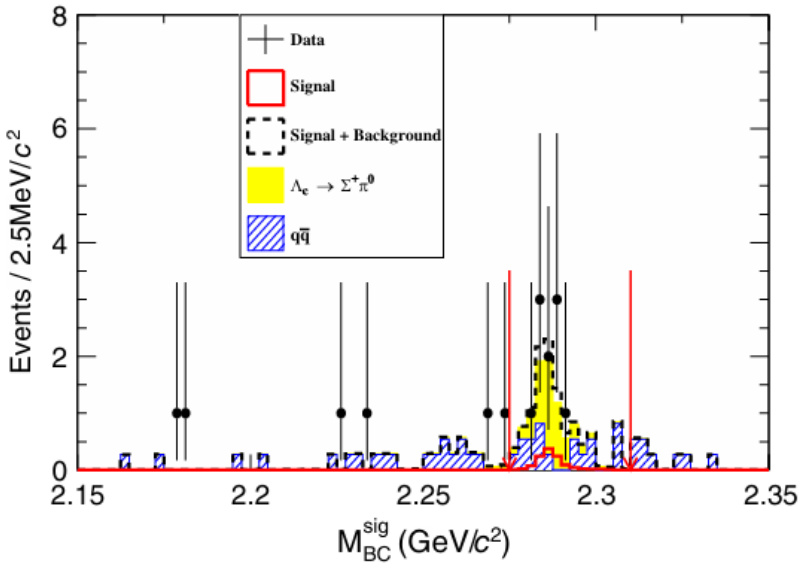
- Weak radiative decays usually receive contributions from both the weak and electromagnetic interactions.
- Many theoretical models predict the BF of $\Lambda_c^+ \to \Sigma^+\gamma$ to be around $10^{-5} - 10^{-4}$.
- The decay proceeds predominantly through a W-exchange diagram accompanied by photon emission from the external quark.
- Belle reported $\mathcal{B}(\Lambda_c^+ \to \Sigma^+\gamma) < 2.6 \times 10^{-4}$.

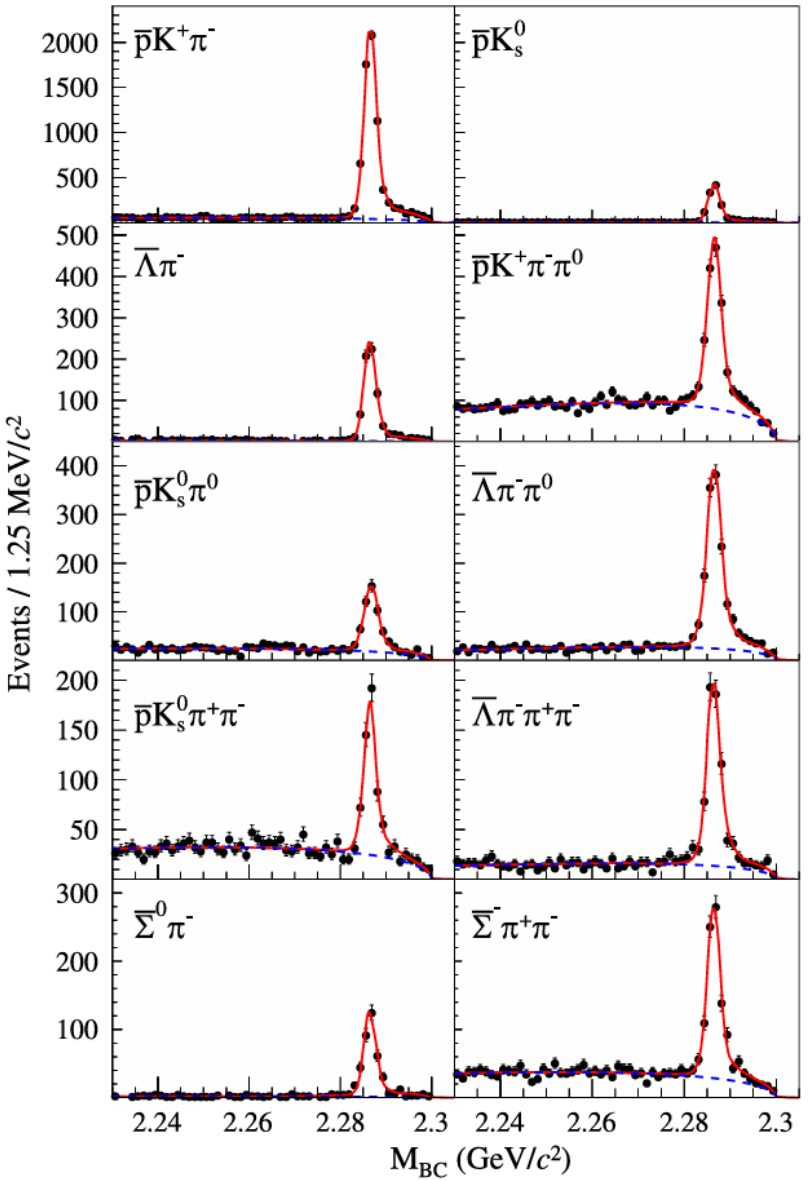


Search for the weak radiative decay $\Lambda_c^+ \to \Sigma^+\gamma$ at BESIII

PRD 107, 052002 (2023)

- data sample: 4.5 fb^{-1}@4.60 − 4.70 GeV
- $\Lambda_c^+ \to \Sigma^+\gamma$ with $\Sigma^+ \to p\pi^0$
- Double-tag method with $\overline{\Lambda}_c^-$ reconstructed in 10 hadronic decay modes
- $\mathcal{B}(\Lambda_c^+ \to \Sigma^+\gamma) < 4.4 \times 10^{-4}$ @ 90% C.L.

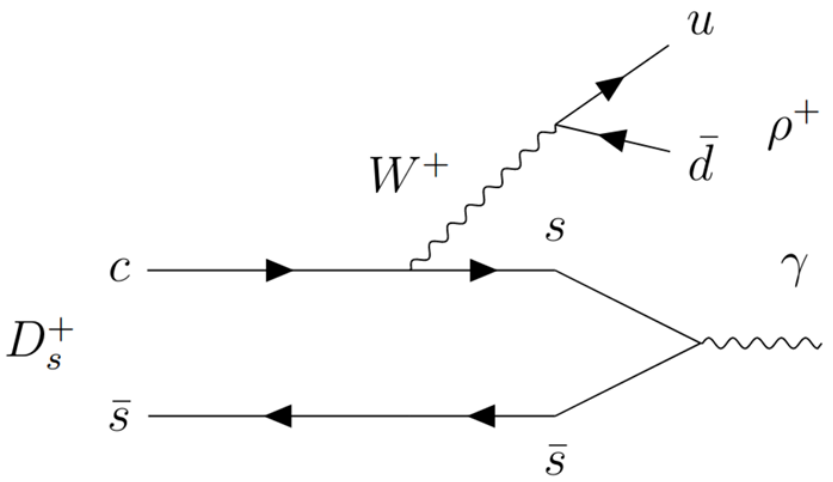




Search for the radiative decay $D_s^+ \to \gamma\rho(770)^+$

JHEP11(2024)119

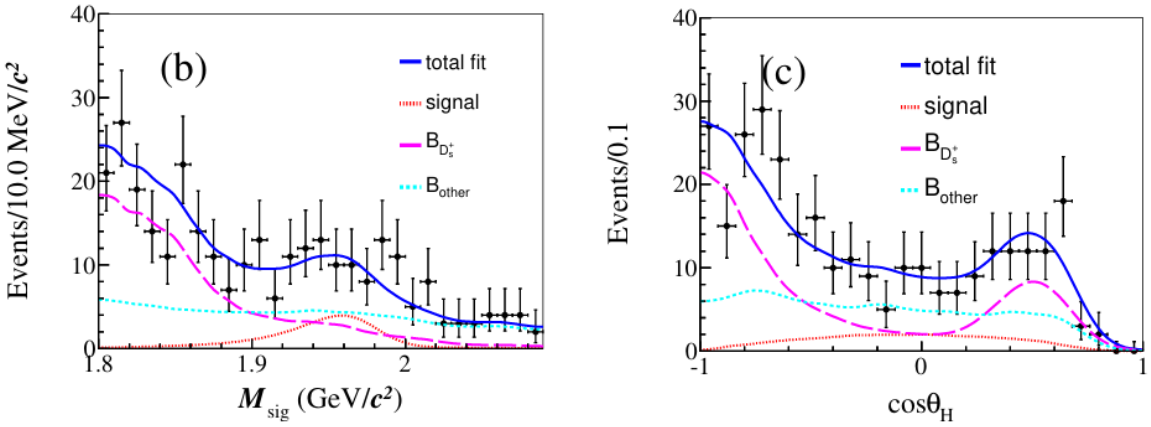
- Non-perturbative processes dominate the $c \to u\gamma$ processes, potentially enhancing BFs up to 10^{-3}.
- The BF of $D_s^+ \to \gamma\rho(770)^+$ can be used to examine the predictions regarding CP asymmetry in charmed meson decays.
- Expected BF of $D_s^+ \to \gamma\rho(770)^+$ ranges from $\mathcal{O}(10^{-5})$ to $\mathcal{O}(10^{-3})$, according to different theoretical models

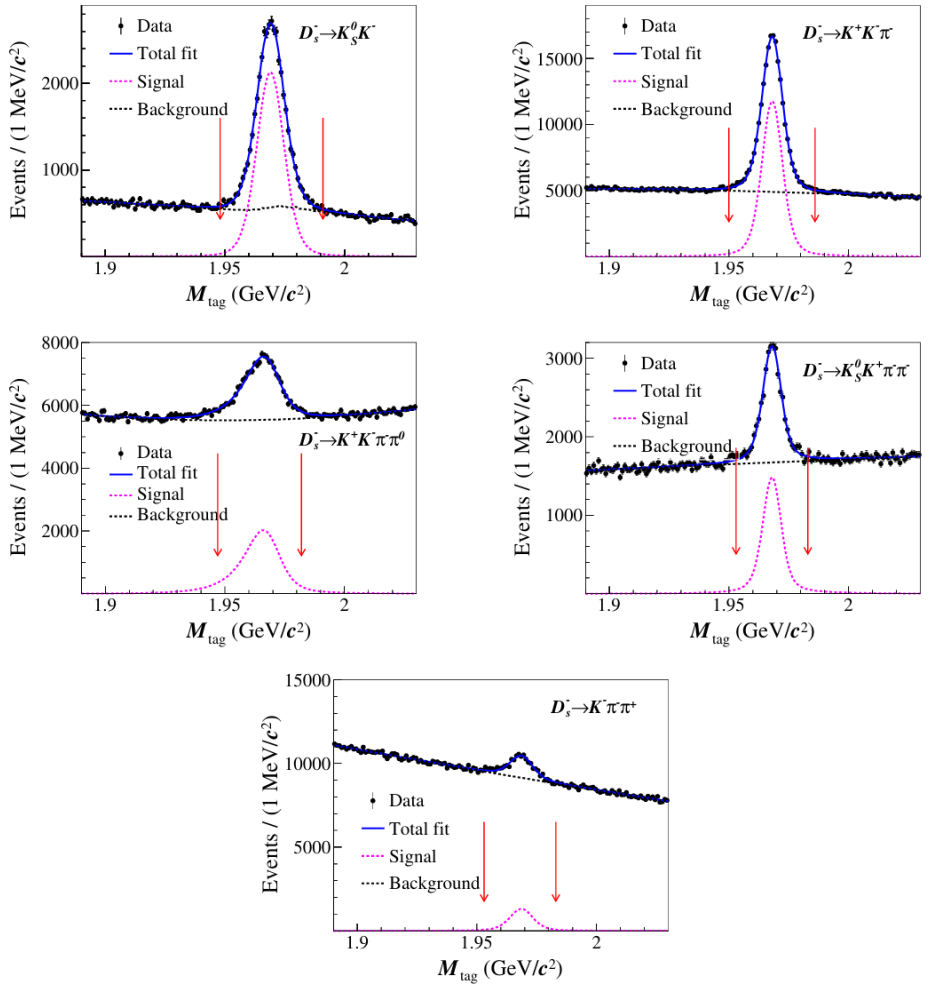


Search for the radiative decay $D_s^+ \to \gamma\rho(770)^+$

JHEP11(2024)119

- data sample: $e^+e^- \to D_s^{\pm}D_s^{*\mp}$, 7.33 fb^{-1}@4.128 – 4.226 GeV
- $D_s^+ \to \gamma\rho(770)^+$ with $\rho(770)^+ \to \pi^+\pi^0$
- Double-tag method with D_s^- reconstructed in 5 hadronic decay modes
- 2D fit to the $M_{\rm sig}$ and $\cos\theta_{\rm H}$ distributions





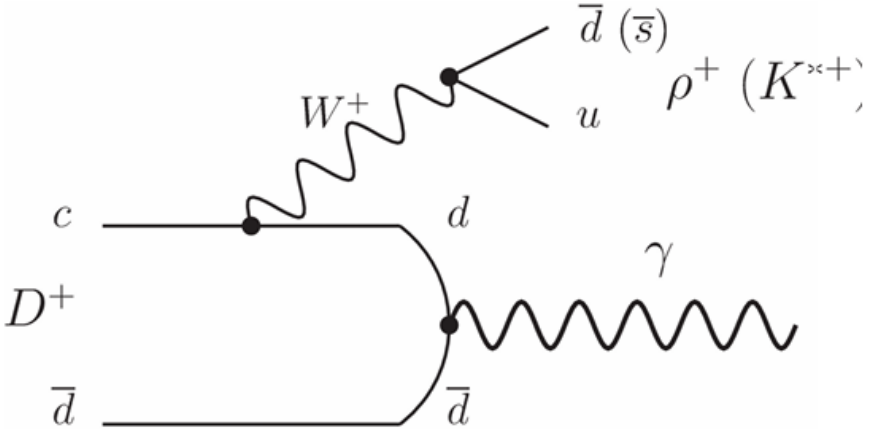
- 2.5σ, $\mathcal{B}(D_s^+ \to \gamma\rho(770)^+) = (2.2 \pm 0.9_{\rm stat} \pm 0.2_{\rm syst})$
- $\mathcal{B}(D_s^+ \to \gamma\rho(770)^+) < 6.1 \times 10^{-4}$ @ 90% C.L.

First search

Search for the radiative decays $D^+ \to \gamma\rho^+$ and $D^+ \to \gamma K^{*+}$

JHEP12(2024)206

- The D^+ meson can be considered "pure" with respect to long-range effects, which are not sensitive to $c \to u$ transitions, unlike the neutral mesons.



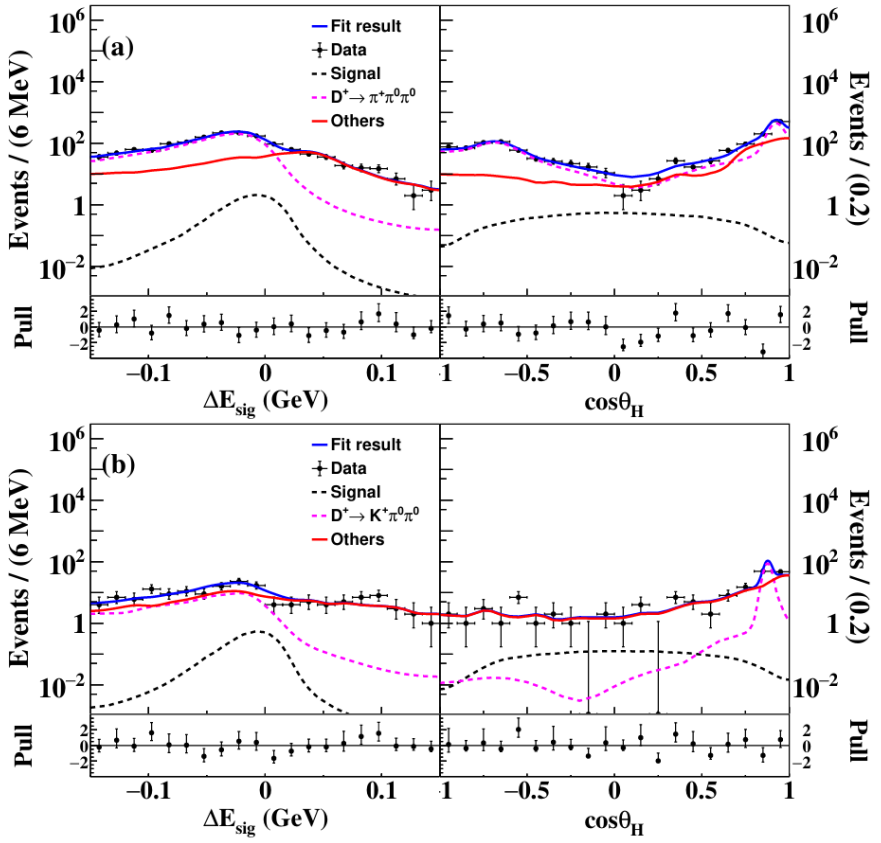
- Predicted BF of the Cabibbo-suppressed process $D^+ \to \gamma\rho^+$ is up to 10^{-5}.
- Expected BF of the doubly Cabibbo-suppressed process $D^+ \to \gamma K^{*+}$ is one order of magnitude lower than that of $D^+ \to \gamma\rho^+$

Search for the radiative decays $D^+ \to \gamma\rho^+$ and $D^+ \to \gamma K^{*+}$

JHEP12(2024)206

- data sample: 20.3 fb^{-1}@3.773 GeV
- $D^+ \to \gamma\rho^+$ with $\rho^+ \to \pi^+\pi^0$ and $D^+ \to \gamma K^{*+}$ with $K^{*+} \to K^+\pi^0$
- Doublt-tag method with D^- reconstructed in 6 hadronic decay modes
- 2D fit to the $\Delta E_{\rm sig}$ and $\cos\theta_{\rm H}$ distributions

Result	$D^+ \to \gamma\rho^+$ $(\times 10^{-5})$	$D^+ \to \gamma K^{*+}$ $(\times 10^{-5})$
PoleDiagram and VMD [1]	$2-6$	$0.1-0.3$
SM [8]	5.0 ± 0.9	—
QCD SM [9]	0.46	—
Hybrid [10]	$0.017-2.33$	$0.048-0.76$
FS [11]	$1.8-4.1$	$0.25-0.5$
Factorization [12]	$0.4-6.3$	$0.03-0.44$
This work	< 1.3	< 1.8



3.6σ deviation

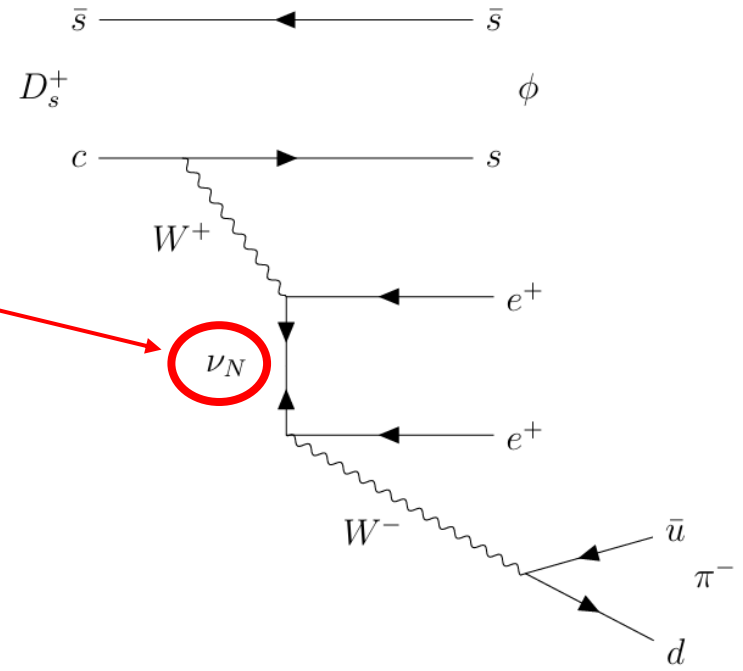
First search

Search for lepton number violating decays of $D_s^+ \to h^- h^0 e^+ e^+$

JHEP01(2025)109

- Lepton Number Violation ($\Delta L \neq 0$) is forbidden in SM.
- Neutrino oscillation $\to m_\nu \neq 0 \to$ New Physics
- Nature of neutrino still unknown: Dirac or Majorana?

- A heave Majorana neutrino can lead to $\Delta L = 2$ LNV processes



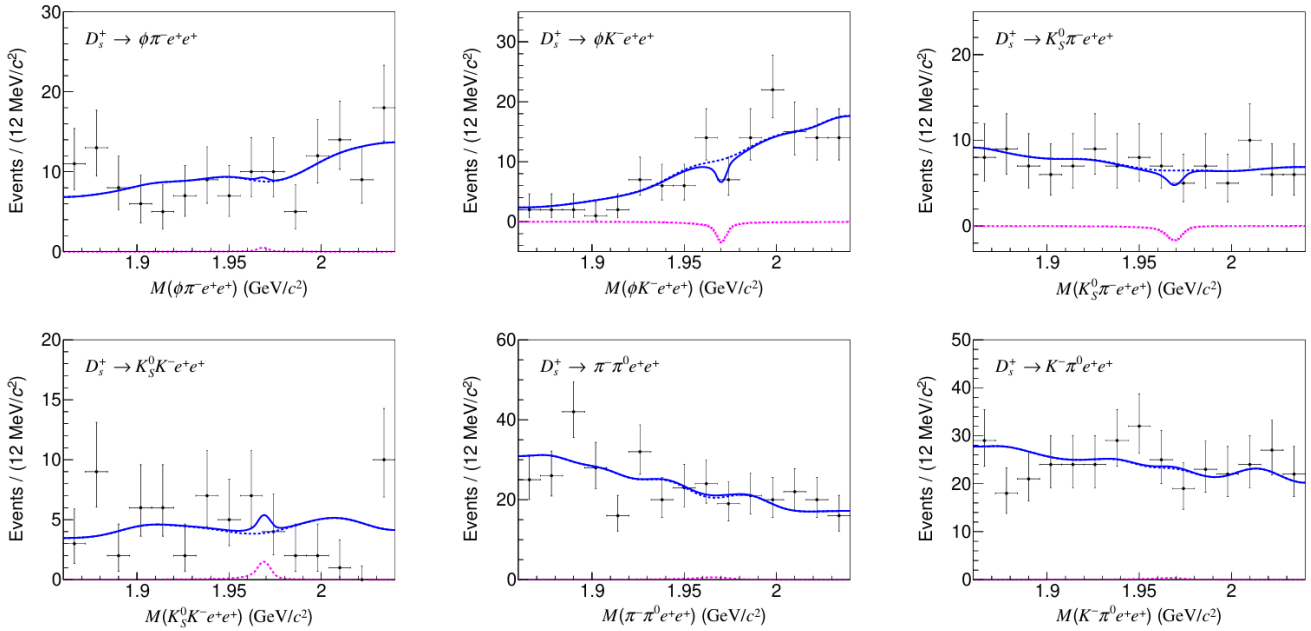
- LNV is introduced in many NP models:
  - 4th quark generation, SO(10) SUSY GUT, exotic Higgs...

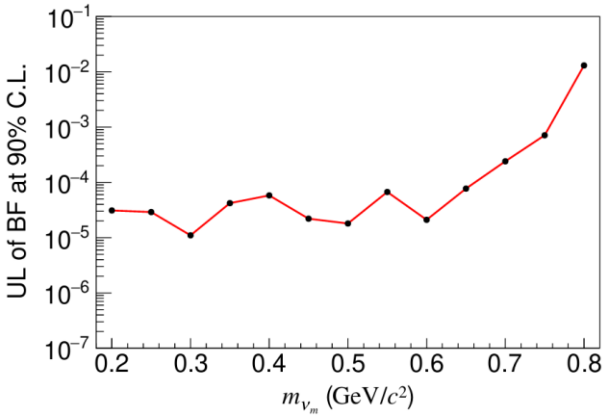
Search for lepton number violating decays of $D_s^+ \to h^- h^0 e^+ e^+$

JHEP01(2025)109

- data sample: $e^+e^- \to D_s^{\pm} D_s^{*\mp}$, $7.33\ \text{fb}^{-1}$@$4.128 - 4.226$ GeV
- Single-tag method
- Fit to the $M(D_s^+)$ distributions
- The Majorana neutrino is searched for in $D_s^+ \to \phi e^+ \nu_m (\to \pi^- e^+)$ based on different m_{ν_m} hypotheses
- ULs as a function of m_{ν_m} obtained using a frequentist method

First search





Decay channel	$\mathcal{B}_{\text{UL}}$
$D_s^+ \to \phi\pi^- e^+ e^+$	6.9×10^{-5}
$D_s^+ \to \phi K^- e^+ e^+$	9.9×10^{-5}
$D_s^+ \to K_S^0 \pi^- e^+ e^+$	1.3×10^{-5}
$D_s^+ \to K_S^0 K^- e^+ e^+$	2.9×10^{-5}
$D_s^+ \to \pi^- \pi^0 e^+ e^+$	2.9×10^{-5}
$D_s^+ \to K^- \pi^0 e^+ e^+$	3.4×10^{-5}

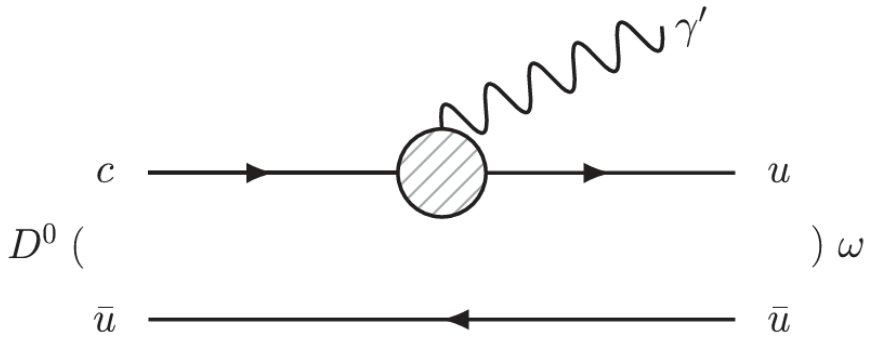
First mass scan in $D \to V l \nu_m$

Search for a massless dark photon in $c \to u\gamma'$ decays

PRD 111, L011103 (2025)

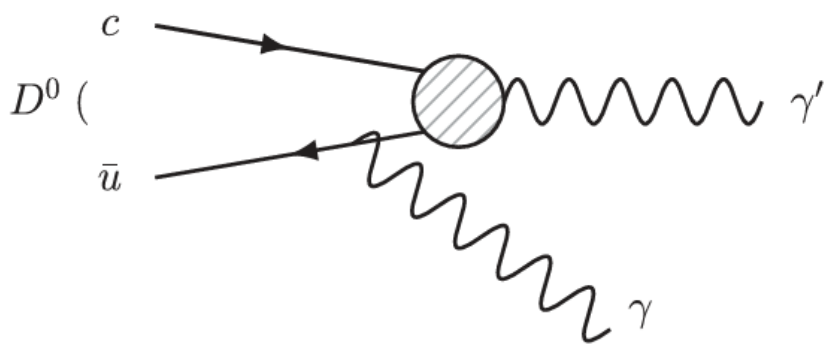
- The dark photon γ' serves as a portal between the SM matter and dark sector.

- The massless dark photon can be searched for in the FCNC $c \to u\gamma'$ decays.



- A dimension-six operator provides a connection between SM fermions and the massless dark photon:

$$\mathcal{L}_{\rm NP} = \frac{1}{\Lambda_{\rm NP}^2}(C_{jk}^{U}\bar{q}_j\sigma^{\mu\nu}u_k\tilde{H} + C_{jk}^{D}\bar{q}_j\sigma^{\mu\nu}d_kH + C_{jk}^{L}\bar{l}_j\sigma^{\mu\nu}e_kH + \text{H.c.})F'_{\mu\nu},$$



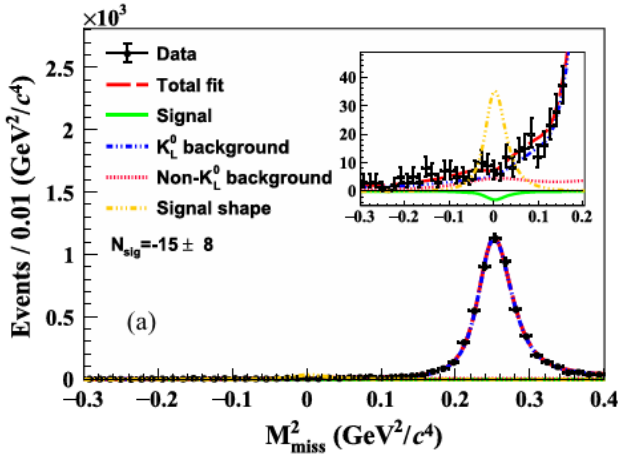
Search for a massless dark photon in $c \to u\gamma'$ decays

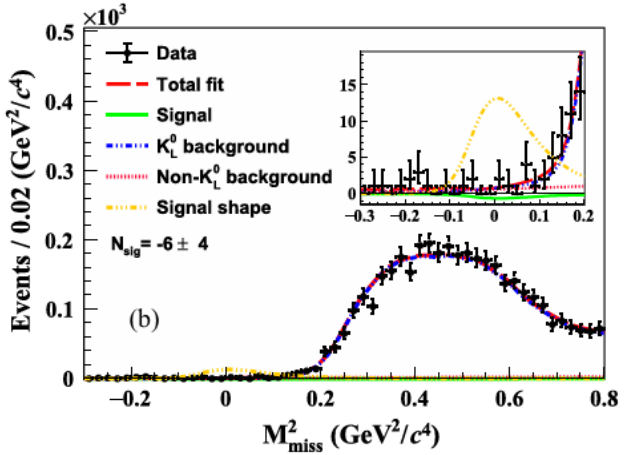
- data sample: 7.9 fb^{-1}@3.773 GeV
- Double-tag method with $\bar{D}^0 \to K^+\pi^-$, $K^+\pi^-\pi^0$, $K^+\pi^-\pi^+\pi^-$
- Fit to the $M^2_{\rm miss}$ distribution

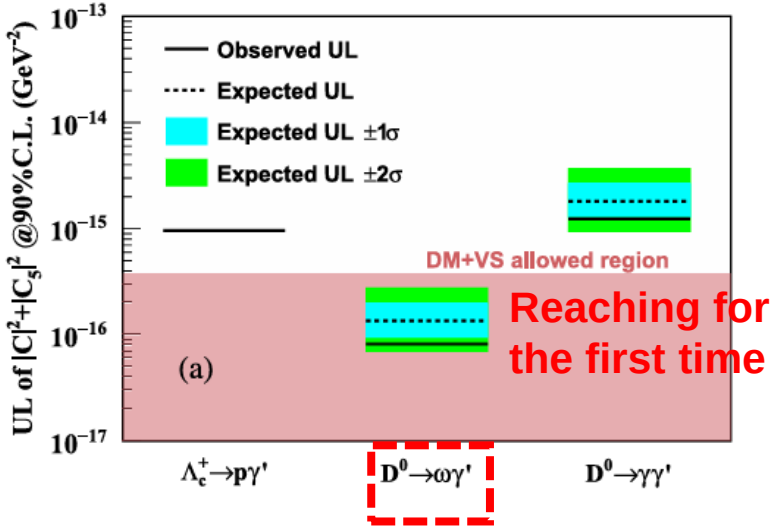
$$M^2_{\rm miss} = |p_{\rm c.m.s.} - p_{\bar{D}^0} - p_{\omega(\gamma)}|^2/c^4$$

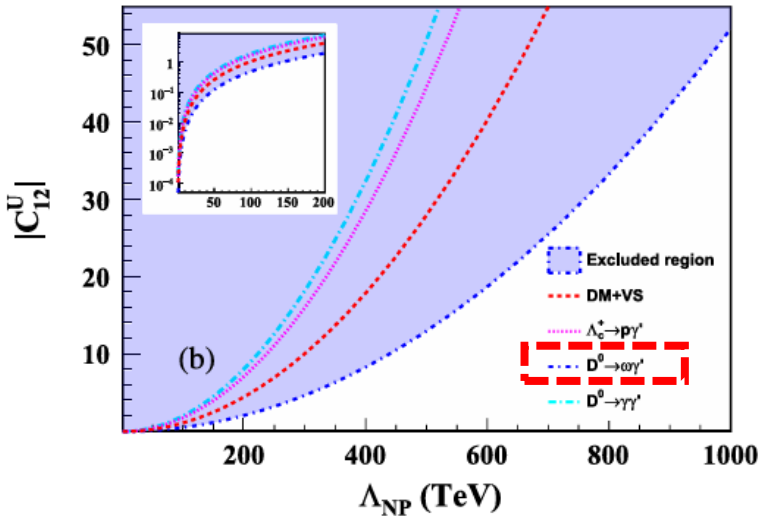
- Upper limits @ 90% C.L. are set for the first time:
  - $\mathcal{B}(D^0 \to \omega\gamma') < 1.1 \times 10^{-5}$
  - $\mathcal{B}(D^0 \to \gamma\gamma') < 2.0 \times 10^{-6}$
- Most stringent constraint on NP energy scale associated with $c \to u\gamma'$ coupling:

$$|\mathbb{C}|^2 + |\mathbb{C}_5|^2 < 8.2 \times 10^{-17}\ \text{GeV}^{-2}$$





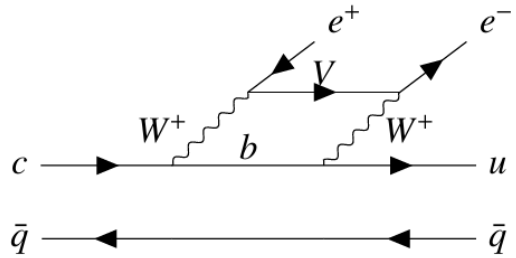




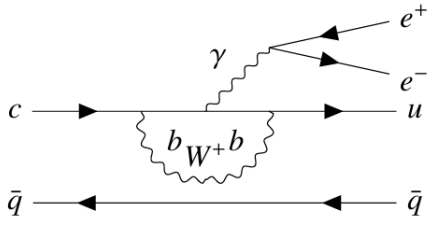
PRD 111, L011103 (2025)

Recent highlight from LHCb

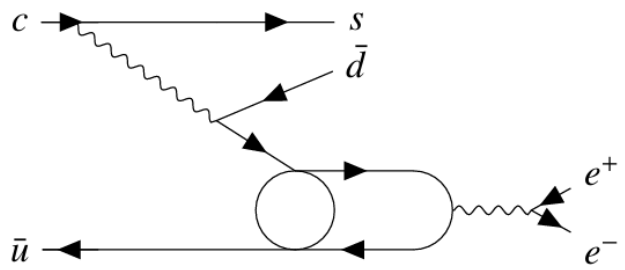
- Short-distance (SD) FCNC transitions via $c \to u$ processes are highly suppressed by the GIM mechanism, leading to BFs of $D \to X l^+ l^-$ decays as low as $\mathcal{O}(10^{-9})$.
- Long-distance (LD) process such as $D \to XY(\to l^+ l^-)$ have BFs up to $\mathcal{O}(10^{-6})$.
- Sensitive to NP!



box diagram



penguin diagram



VMD

- LHCb recently reported the first observation of $D^0 \to \pi^+\pi^-[e^+e^-]_{\phi,\rho^0/\omega}$

PRD 111, L091101 (2025)

Search for D^0 meson decays to $\pi^+\pi^-e^+e^-$ and $K^+K^-e^+e^-$ final states

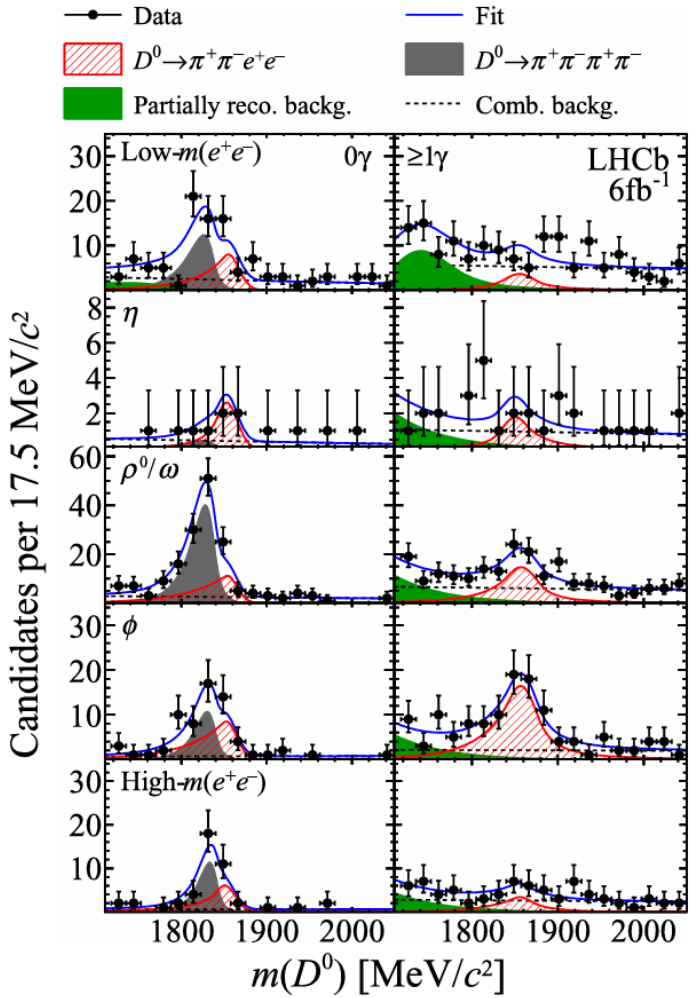


FIG. 1. Mass distributions of selected $D^0 \to \pi^+\pi^-e^+e^-$ candidates in the low-$m(e^+e^-)$, η, ρ^0/ω, ϕ and high-$m(e^+e^-)$ regions in the (left, 0γ) no-brem and (right, $\geq 1\gamma$) with-brem categories. Fit projections are also shown.

➢data sample: 6 fb^{-1}@13 TeV

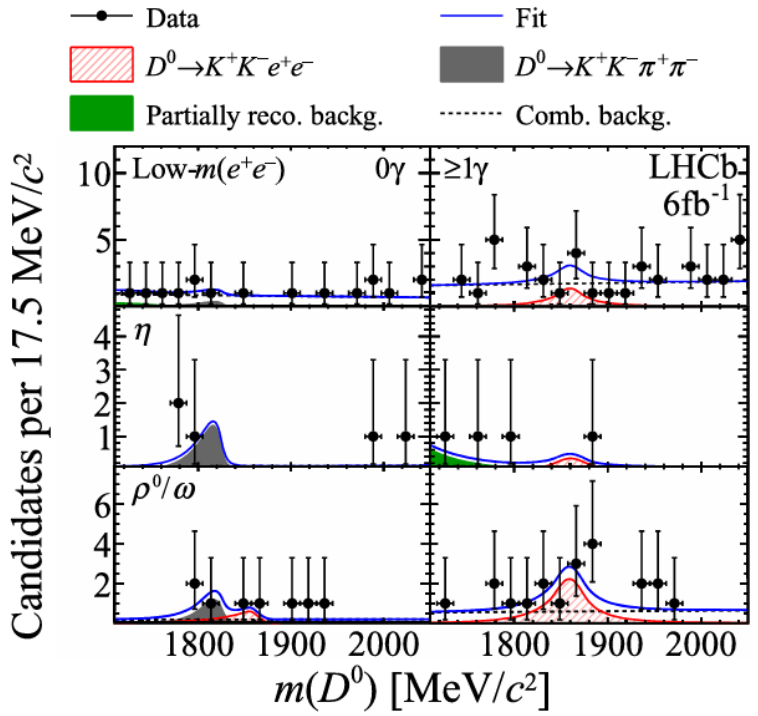


FIG. 2. Mass distributions of selected $D^0 \to K^+K^-e^+e^-$ candidates in the low-$m(e^+e^-)$, η and ρ^0/ω regions in the (left) no-brem (0γ) and (right) with-brem ($\geq 1\gamma$) categories. Fit projections are also shown.

PRD 111, L091101 (2025)

Search for D^0 meson decays to $\pi^+\pi^-e^+e^-$ and $K^+K^-e^+e^-$ final states

$m(e^+e^-)$ region	[MeV/c^2]	Yield	$\mathcal{S}$
	$D^0 \to \pi^+\pi^-e^+e^-$		
Low mass	$2m_\mu$–525	37 ± 13	2.8σ
η	525–565	10 ± 7	1.6σ
ρ^0/ω	565–950	97 ± 21	5.5σ
ϕ	950–1100	100 ± 18	8.1σ
High mass	> 1100	30 ± 11	2.9σ
	$D^0 \to K^+K^-e^+e^-$		
Low mass	$2m_\mu$–525	4 ± 8	1.2σ
η	525–565	1 ± 2	1.1σ
ρ^0/ω	> 565	12 ± 7	2.2σ

PRD 111, L091101 (2025)

First observation of

$$D^0 \to \pi^+\pi^-[e^+e^-]_{\phi,\,\rho^0/\omega}$$

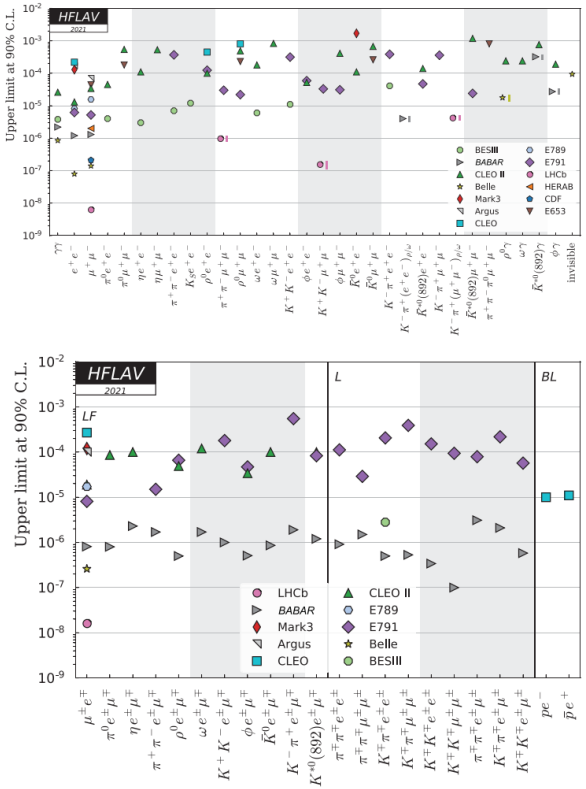
$m(\ell^+\ell^-)$ region	[MeV/c^2]	$\mathcal{B}$ [10^{-7}]	
		$D^0 \to \pi^+\pi^-e^+e^-$	$D^0 \to \pi^+\pi^-\mu^+\mu^-$ [20]
Low mass	$2m_\mu$–525	$<4.8(5.4)$	$0.78 \pm 0.19 \pm 0.05 \pm 0.08$
η	525–565	$<2.3(2.7)$	$<0.24(0.28)$
ρ^0/ω	565–950	$4.5 \pm 1.0 \pm 0.7 \pm 0.6$	$4.06 \pm 0.33 \pm 0.21 \pm 0.41$
ϕ	950–1100	$3.8 \pm 0.7 \pm 0.4 \pm 0.5$	$4.54 \pm 0.29 \pm 0.25 \pm 0.45$
High mass	>1100	$<2.0(2.2)$	$<0.28(0.33)$
		$D^0 \to K^+K^-e^+e^-$	$D^0 \to K^+K^-\mu^+\mu^-$ [20]
Low mass	$2m_\mu$–525	$<1.0(1.1)$	$0.26 \pm 0.12 \pm 0.02 \pm 0.03$
η	525–565	$<0.4(0.5)$	$<0.07(0.08)$
ρ^0/ω	>565	$<2.2(2.5)$	$1.20 \pm 0.23 \pm 0.07 \pm 0.12$

First lepton universality tests with such decays

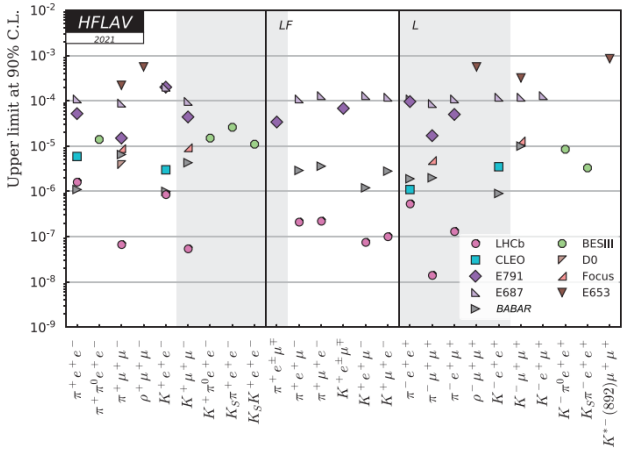
- Belle also reported the search of $D^0 \to \pi^+\pi^-e^+e^-$ decay recently, but with no significant signal observed. [arXiv:2507.05050 [hep-ex]]

Prospects

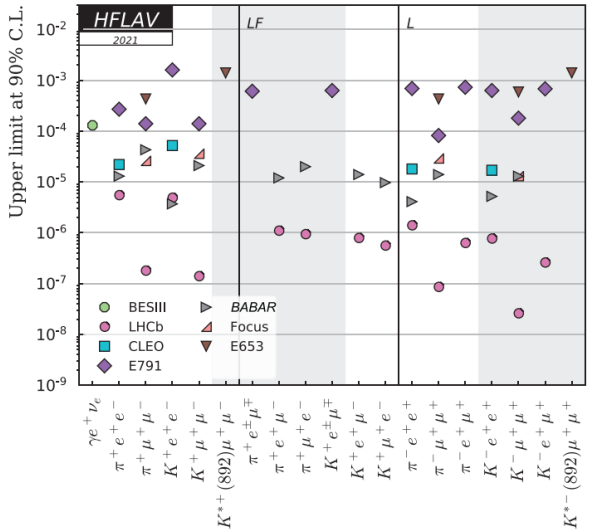
Averages of b-hadron, c-hadron, and τ-lepton properties as of 2021. (HFLAV Collaboration). Phys. Rev. D. 107, 052008 (2023)



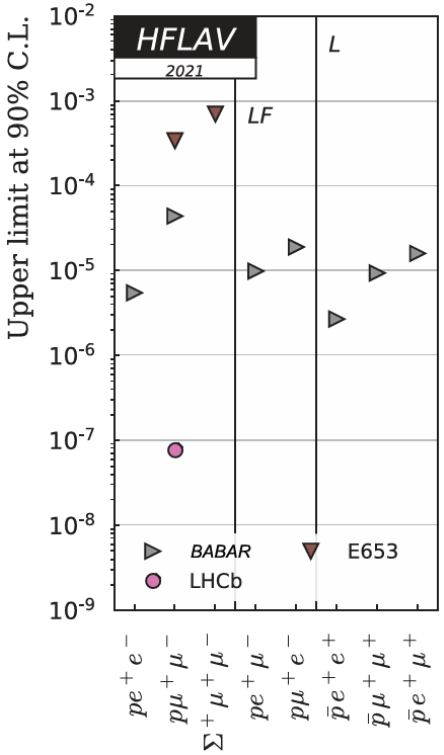
D^0



D^+



D_s



Λ_c^+

Still lots of unexplored decays...

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 $D^+ \to K^- e^+ e^+$.

Prospects

- Works about rare charm hadron decays ongoing:
  - Absolute measurements of the branching fractions of $D^0 \to \gamma \overline{K}^{*0}$ and $D^0 \to \gamma\phi$ [BAM-592]
  - Search for the radiative decay $D^0 \to \gamma\omega$ [BAM-708]
  - Search for the radiative decays $D^0 \to \gamma \overline{K}_1^0(1270)$ and $D^+ \to \gamma K_1^+(1270)$ [BAM-837]
  - Search for the radiative decays $D_s^+ \to \gamma K^*(892)^+$ [BAM-928]
  - Search for the radiative decays $D_s^+ \to \gamma K_1^+(1270)$ [early stage]
  - Study of $D^0 \to \gamma\rho^0$ with deep learning [early stage]
  - Search for rare decay of $\Lambda_c^+ \to p\gamma$ [early stage]
  - Search for rare decays of $D \to h(h^{(\prime)})e^+e^-$ [BAM-1018]
  - Search for FCNC process $D^+ \to h^+e^+e^-$ and LNV process $D^+ \to h^-e^+e^+$ [doc-1431]

Prospects

- Works about rare charm hadron decays ongoing:
  - Search for baryon- and lepton-number-violating $D^{\pm}$ decays [doc-1629]
  - Search for baryon- and lepton-number-violating D_s^+ decays [doc-1706]
  - Search for four-body LFV D_s^+ decays [early stage]
  - Search the CLFV process $D^0/\bar{D}^0 \to e\tau$ [doc-1614]
  - Search for the rare decays $D_s^+ \to K^+ \nu\bar{\nu}$ [early stage]
  - Search for massless particle beyond the SM in $D^+ \to \pi^+$ + invisible decay [BAM-993]
  - Search the light neutralino $\tilde{\chi}_1^0$ with $D^0 \to \bar{\Xi}^0 \tilde{\chi}_1^0 + c.c.$ [early stage]
  - Search the light neutralino $\tilde{\chi}_1^0$ with $D^0 \to \Lambda \tilde{\chi}_1^0 + c.c.$ [early stage]
  - Search the light neutralino $\tilde{\chi}_1^0$ with $D^+ \to p \tilde{\chi}_1^0 + c.c.$ [early stage]

Summary

- BESIII has performed wide range studies of rare charm hadron decays, with many first searches or best limits.

- BESIII has collected the 20.3 fb^{-1} $\psi(3773)$ data samples, and there will be more data of $\Lambda_c\bar{\Lambda}_c$ in the near future. BESIII possesses great potentials in searches for rare charm hadron decays.

- The application of new techniques (e.g., deep learning, novel charm meson tagging method) enhances search sensitivity.

Thanks!