Charm

Search for FCNC decays
@ BESIII

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202/08/27

Outline

- Motivation
- Current status
- BESIII charm datasets
- A selection of recent charm FCNC-related results:
  - $D^0 \to \pi^0 \nu\bar{\nu}$ [PRD 105, L071102 (2022)]
  - $D_s^+ \to h(h')e^+e^-$ [arXiv:2404.05973, accepted by PRL]
  - $D_s^+ \to \gamma\rho(770)^+$ [arXiv:2408.03980, submitted to JHEP]
- Prospects & summary

Summary of charm decays

Charm provide a unique environment for testing the SM rare/forbidden decays and searching for NP

Complementary information to B and K sectors with down-type quarks

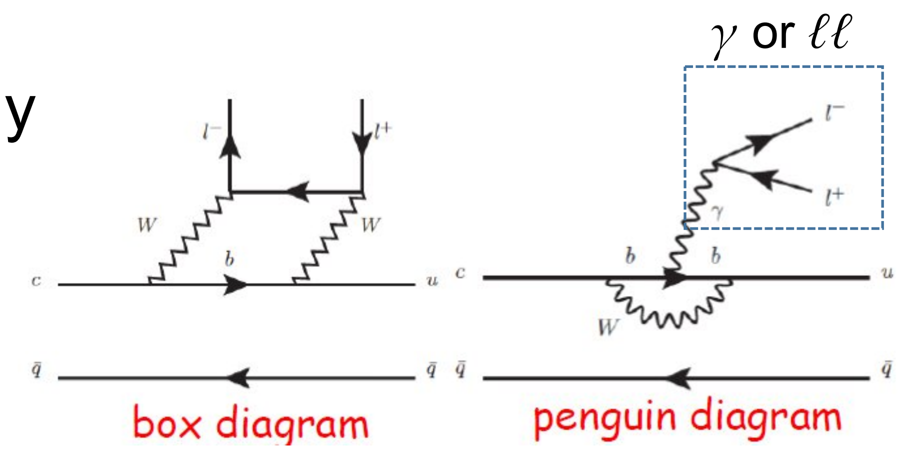
BFs expected in SM

- 10^{-0}
- 10^{-1}
- 10^{-2} Cabibbo favor
- 10^{-3} Single Cabibbo suppressed
- 10^{-4} Doubly Cabibbo suppressed
- 10^{-5} Radiative decays: $D^0 \to K^{*0}\gamma/\phi\gamma/\omega\gamma/\rho\gamma$; $D^+_{(S)} \to K^{*+}\gamma/\rho^+\gamma$
- 10^{-6}
- 10^{-7} Long distance:
- 10^{-8} Vector meson Dominance (SM): $D^{0+} \to \gamma\gamma/VV'(l^+l^-)/\ hV(l^+l^-)/\ hh'V(l^+l^-)$
- 10^{-9}
- 10^{-10} Short distance FCNC (SM+NP): $D^{0/+} \to \gamma\gamma/Vl^+l^-/hl^+l^-/hh'l^+l^-$; $D^0 \to \mu^+\mu^-/e^+e^-$
- 10^{-11}
- 10^{-12}
- 10^{-13}
- 10^{-14} (NP)
- 10^{-15} Forbidden decays: LNV, LFV, BNV: $D \to (hh)\mu^+\mu^+/(hh)e^+e^+$; $D \to (h)\mu^+e^-$; $D \to (h)pe^-$

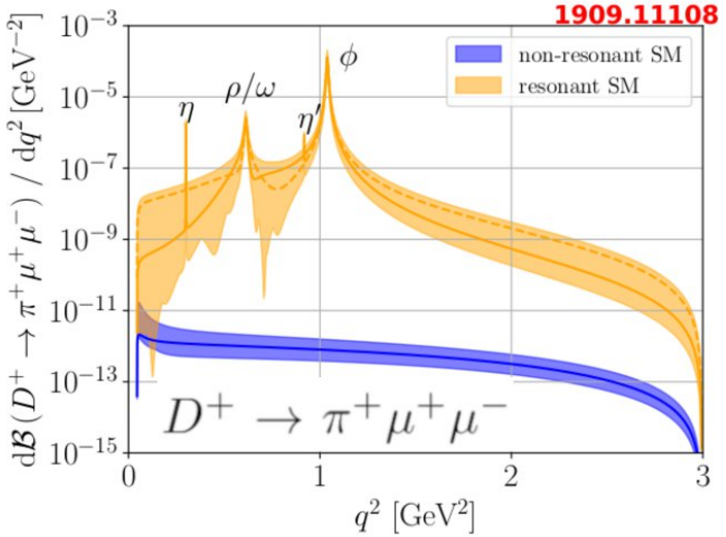
Rare decays

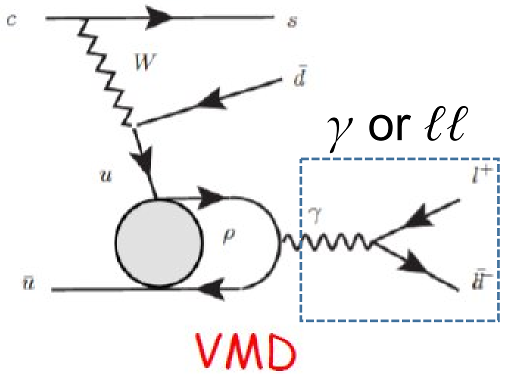
Flavor Changing Neutral Currents in charm

- $c \to u$ processes forbidden at tree level in SM, only allowed in loop and box diagrams
  - Strongly suppressed due to GIM cancellation:
  - Expected SM BF ~O(10^{-9})
  - NP might manifest in the loops

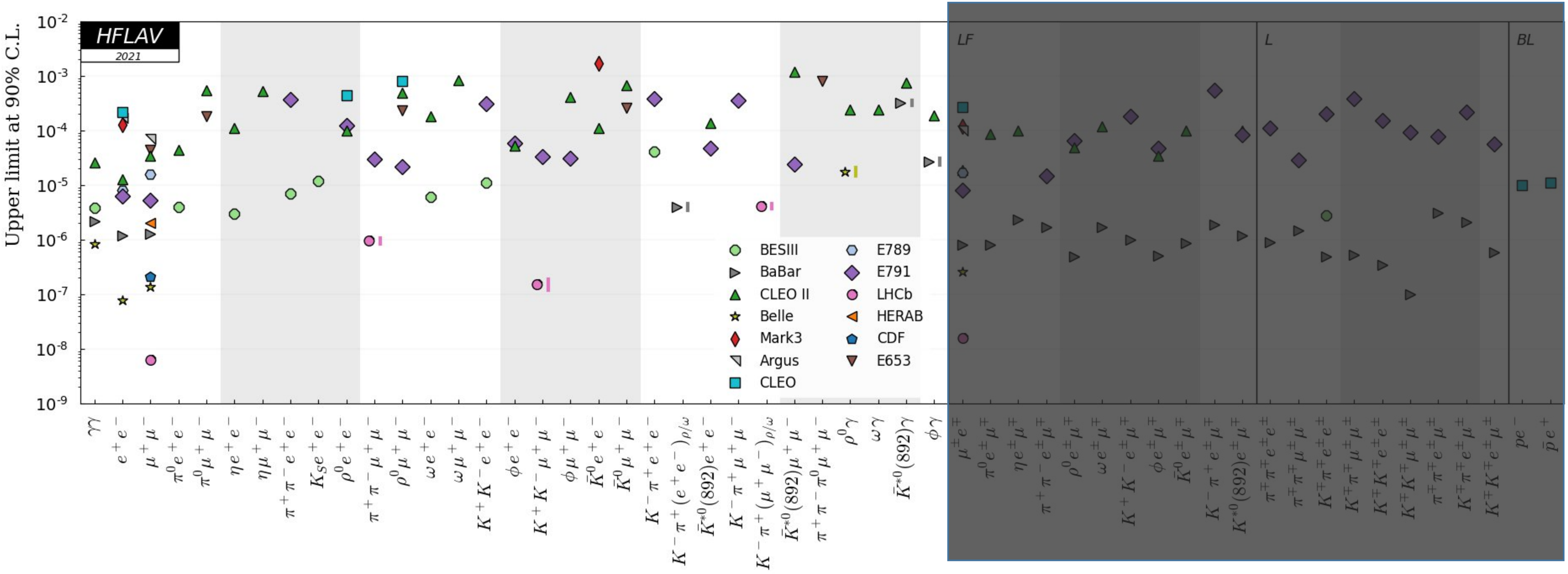


- $D \to X\ell^+\ell^-$ & $D \to \gamma X$ dominated by Long-Distance contributions
  - Vector Meson Dominance (VMD)
  - BF ~O(10^{-6}) for $D \to X\ell^+\ell^-$
  - BF up to 10^{-4} for $D \to \gamma X$
- No VMD in $D \to X\nu\bar{\nu}$



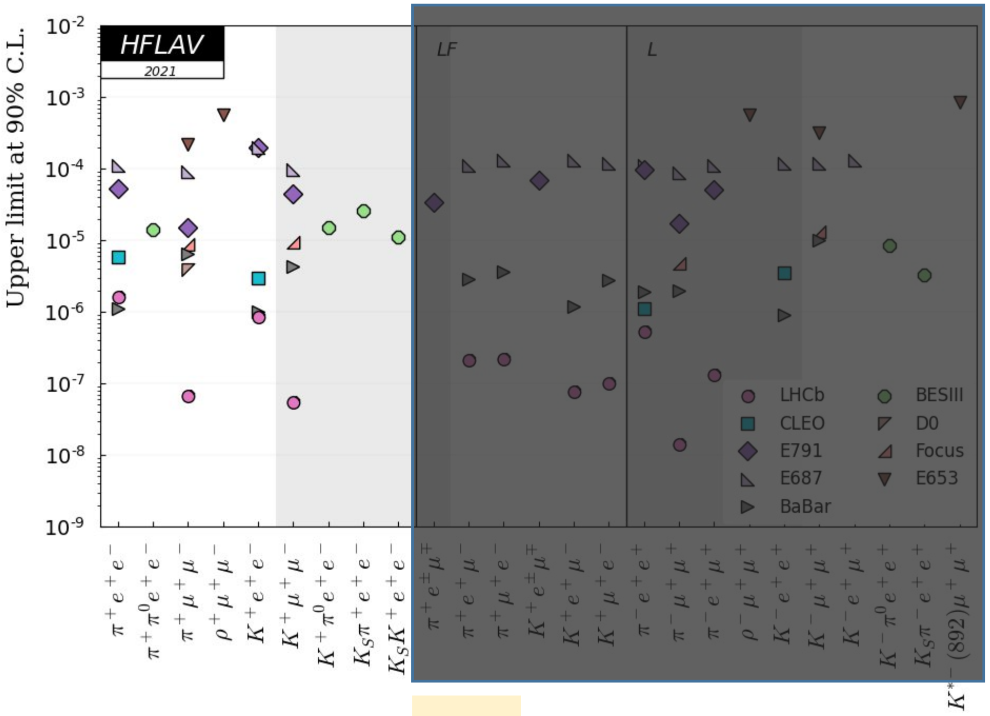


Results on rare charm decays (D^0)

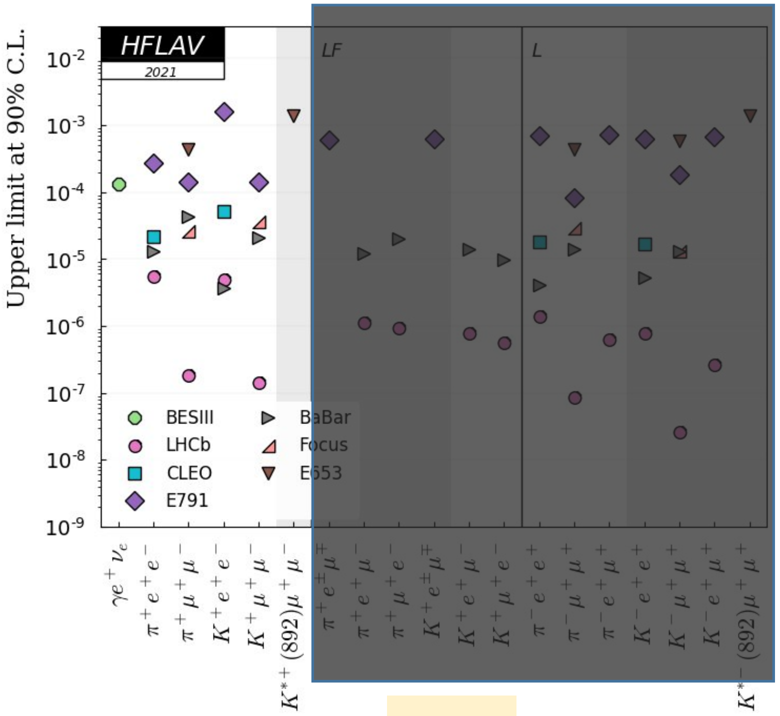


https://hflav-eos.web.cern.ch/hflav-eos/charm/rare/Spring2021/rare_charm.html

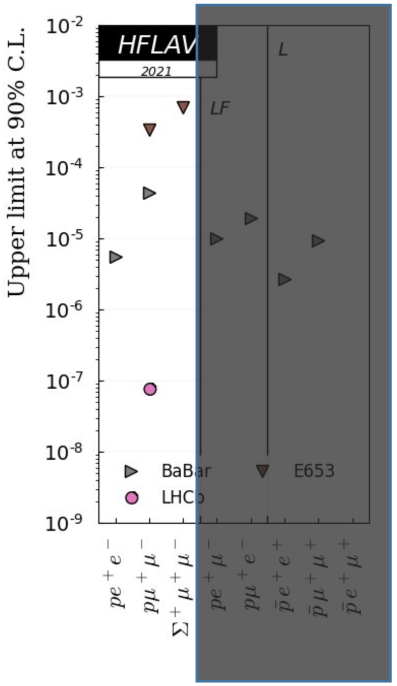
Results on rare charm decays



D^+



D_s^+

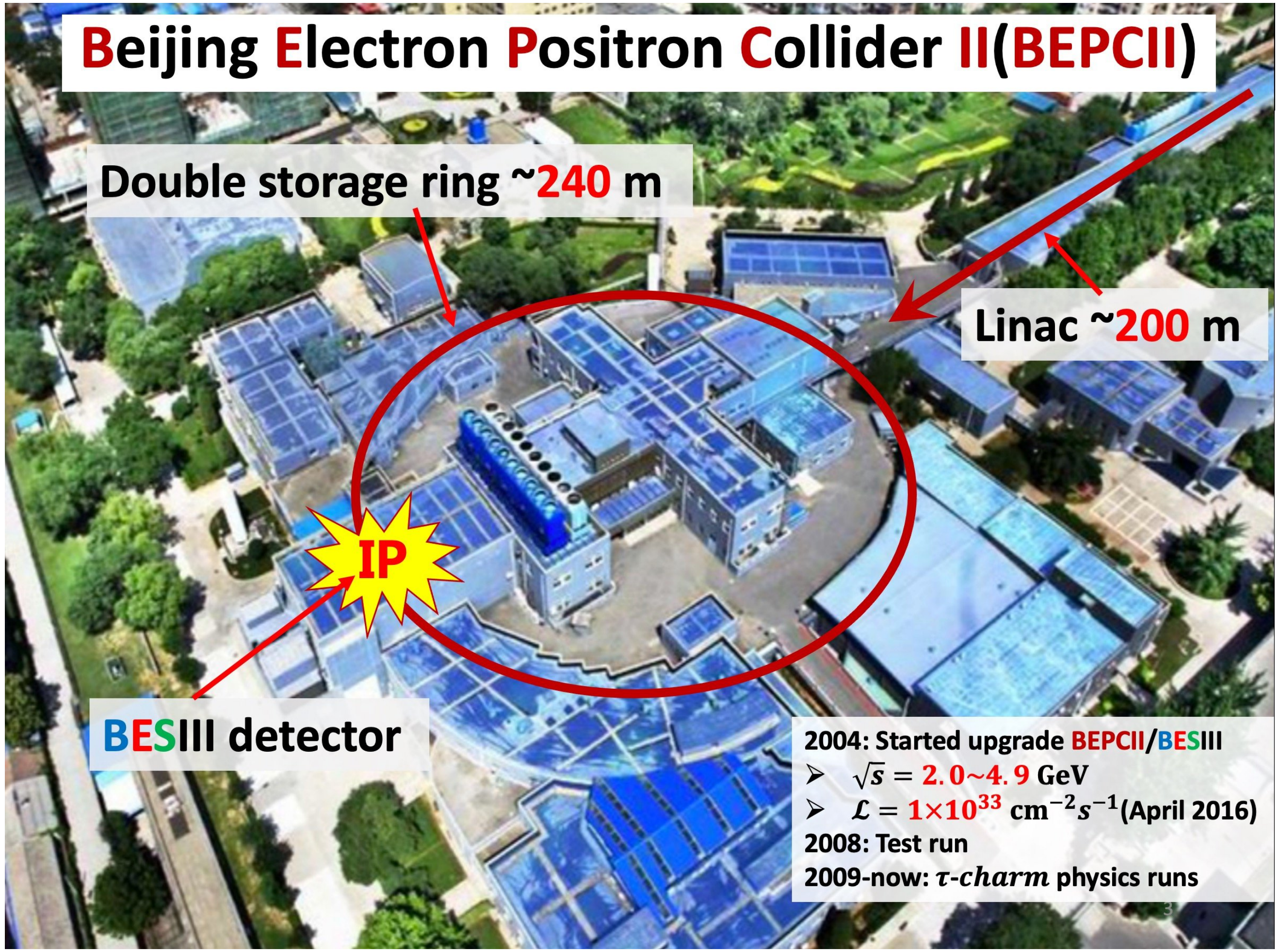


Λ_c^+

Still lots of unexplored channels...

https://hflav-eos.web.cern.ch/hflav-eos/charm/rare/Spring2021/rare_charm.html

BEPCII & BESIII



Electromagnetic CsI(Tl) Calorimeter (EMC)

σE%$\neg$ 2.5± ™ 1 GeV (barrel)

σE%$\neg$ 5± ™ 1 GeV (end-caps)

Time-of-Flight (TOF)

$\sigma_t > 90$ ps (barrel)

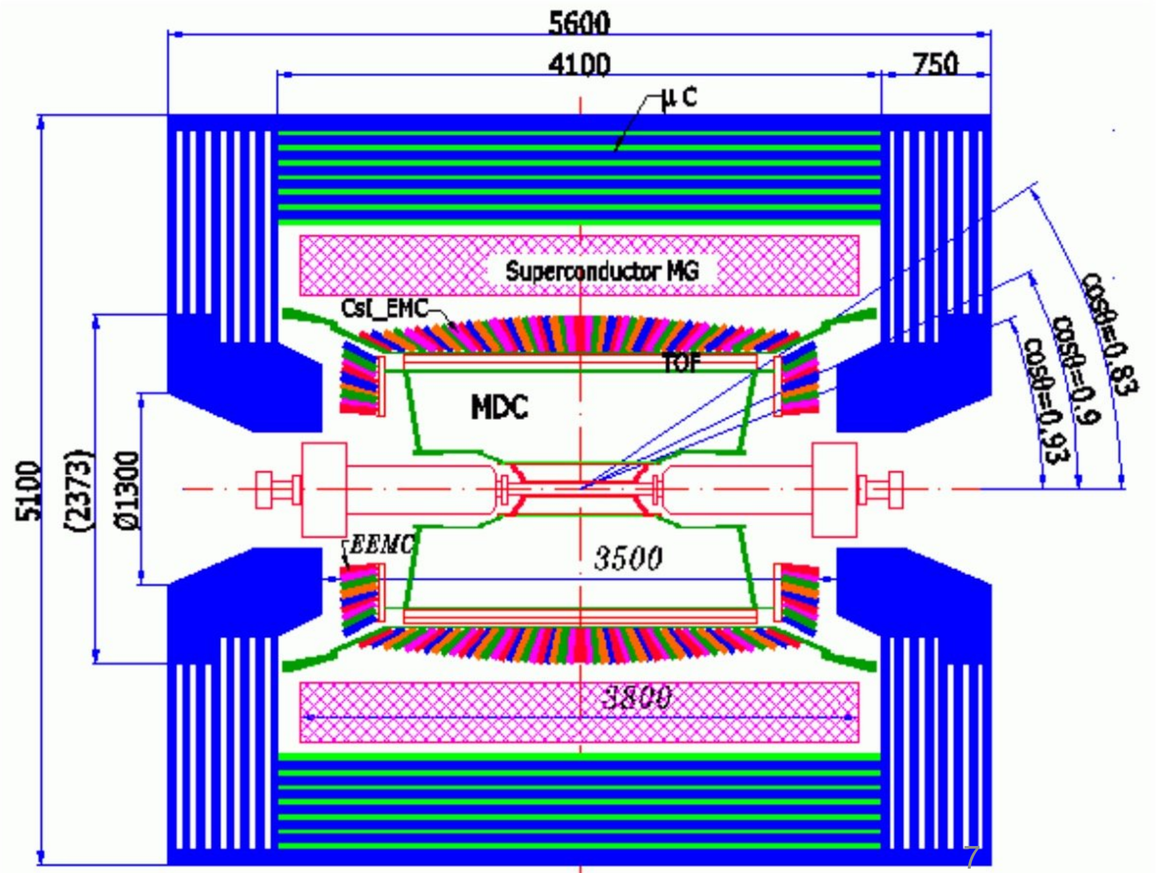
$\sigma_t > 120$ ps (end-caps)

Main Drift Chamber (MDC)

$\sigma r\phi > 130$ μm (single wire)

σp_t% > 0.5± ™ 1 GeV

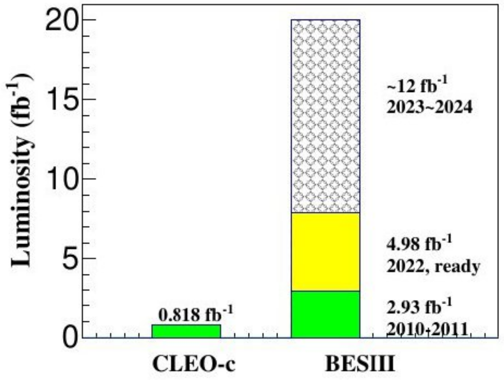
Superconducting solenoid (1 Tesla)

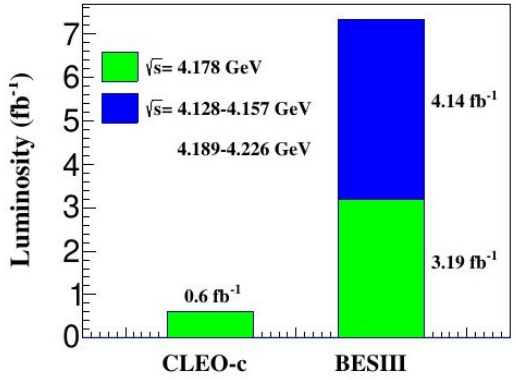


M. Ablikim *et al.* (BESIII Collaboration), Nucl. Instr. Meth. A614, 345 (2010)

Charm datasets @ BESIII

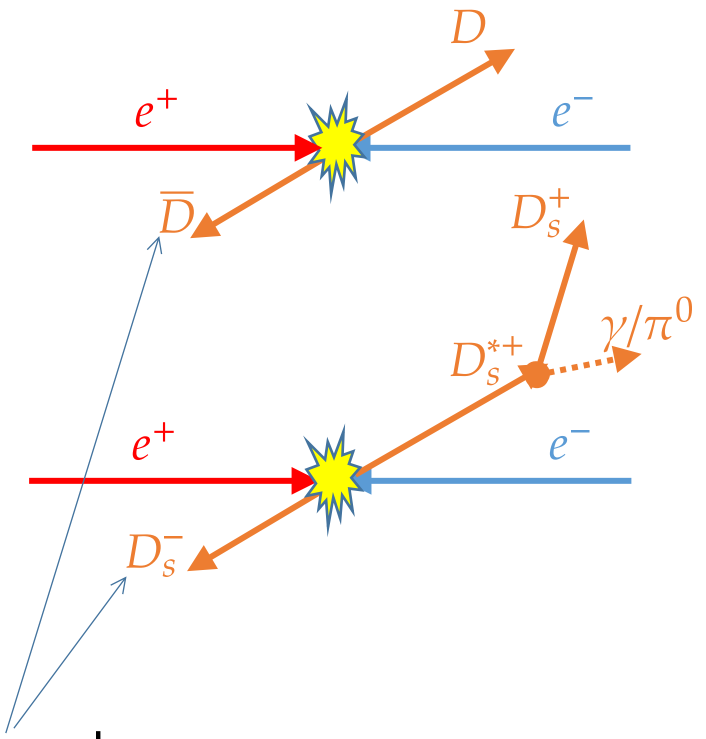
- Pairs of charm hadrons produced near threshold w/o additional hadrons





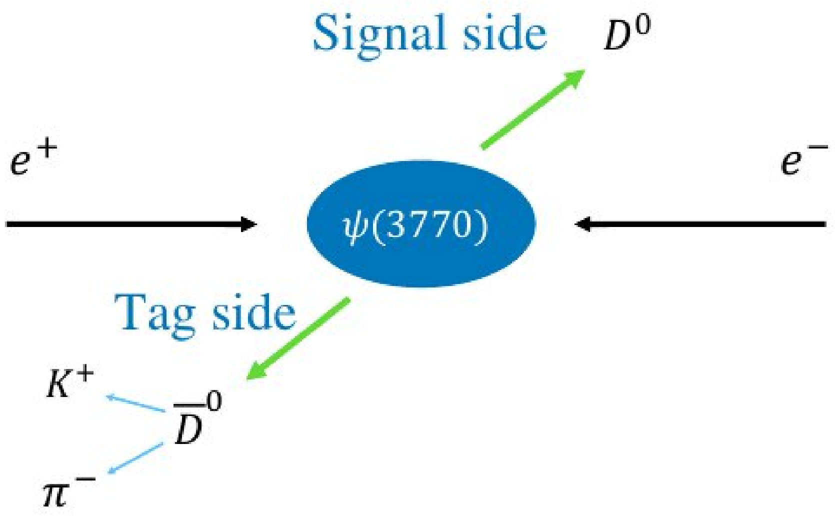
  - $e^+e^- \to \psi(3770) \to D\bar{D}$, $\mathcal{L}_{\text{int}}$ =2.93+4.98 (+12) fb^{-1}
  - $e^+e^- \to D_s D_s^*$, $\sqrt{s} = 4.128 - 4.226$ GeV, $\mathcal{L}_{\text{int}}$=7.33 fb^{-1}

- Advantages:
  - Low background level
  - Full event info, neutrino kinematics can be inferred
  - Absolute branching fraction measurement possible with one $\overline{D}_{(s)}$ tagged
  - Superb EMC performance on e / γ / π^0



Double-Tag method

- Fully reconstructed $\overline{D}$ at tag side (**ST**)
- Requiring signal decay at the other side (**DT**)



ST yields:

$$N^{\mathrm{ST}}_{D_{(s)}} = 2 \times N_{D\bar{D}} \times B_{ST} \times \varepsilon_{ST}$$

DT yield:

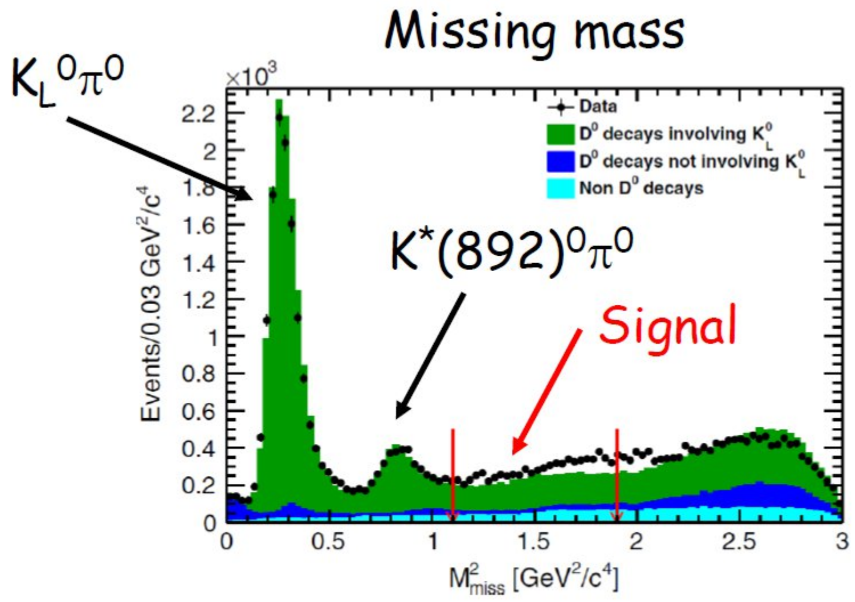
$$N^{\mathrm{signal}}_{\mathrm{DT}} = 2 \times N_{D\bar{D}} \times B_{ST} \times B_{sig} \times \varepsilon_{ST,sig}$$

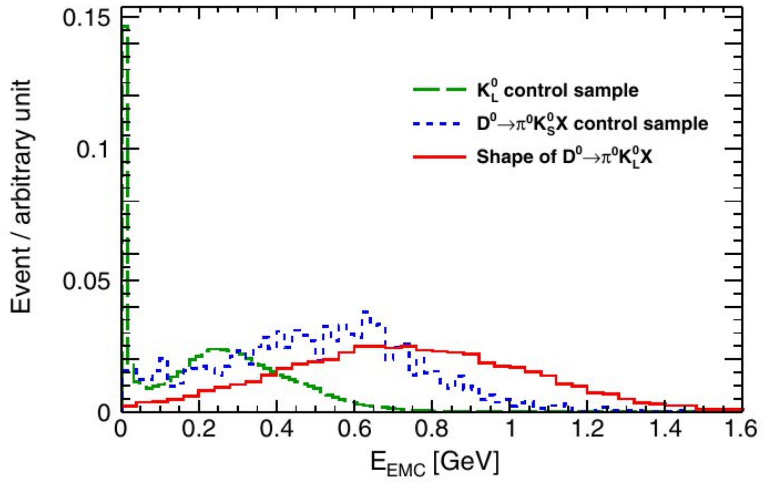
The signal branching fraction:

$$B_{\mathrm{sig}} = \frac{N^{\mathrm{signal}}_{\mathrm{DT}}}{N^{\mathrm{ST}}_{D_{(s)}} \times \varepsilon}$$

$D^0 \to \pi^0 \nu\bar{\nu}$

- First search on charm hadron decays into $\nu\bar{\nu}$ final states
- Reliable modeling of K_L^0 backgrounds crucial for this analysis with $D^0 \to \pi^0 K_L^0 X$ decays as dominating residual background
- Two steps based on data-driven methods:
  - Model K_L^0 energy deposit ($E_{\mathrm{EMC}}^{K_L^0}$) using high-purity samples of $J/\psi \to \phi K^\pm \pi^\mp K_L^0$ and $J/\psi \to K^\pm \pi^\mp K_L^0$
  - Model energy deposit of X (E_{EMC}^{X}) and K_L^0 kinematics using data sample of $D^0 \to \pi^0 K_S^0(\pi^+\pi^-)X$
  - $E_{\mathrm{EMC}} = E_{\mathrm{EMC}}^{K_L^0} + E_{\mathrm{EMC}}^{X}$

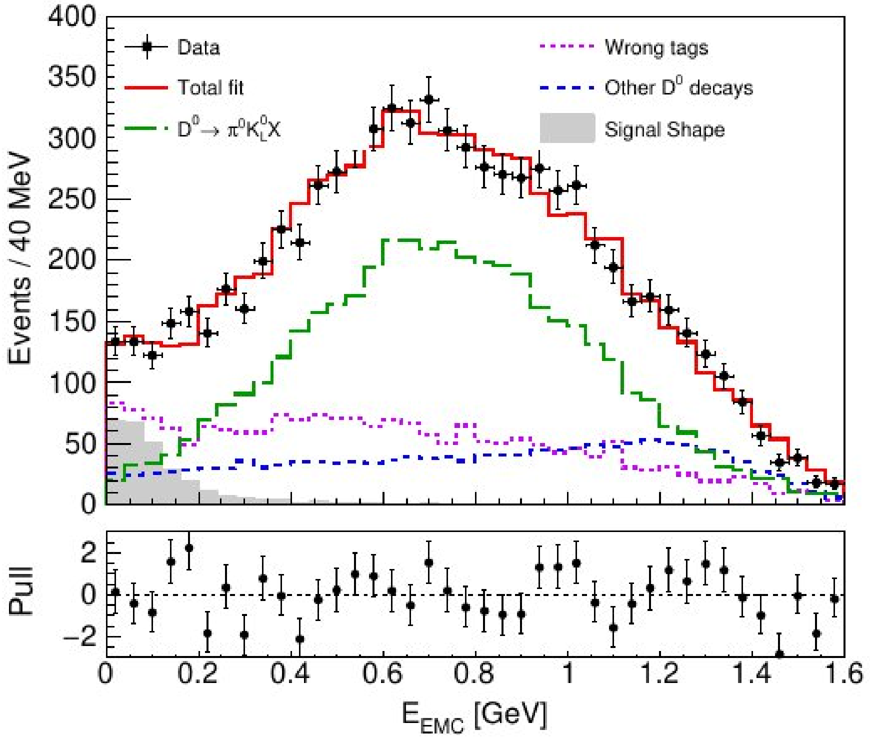




PRD 105 (2022) L071102

$D^0 \to \pi^0 \nu\bar{\nu}$

Fit with MC shape
$N_{sig} = 14 \pm 30$

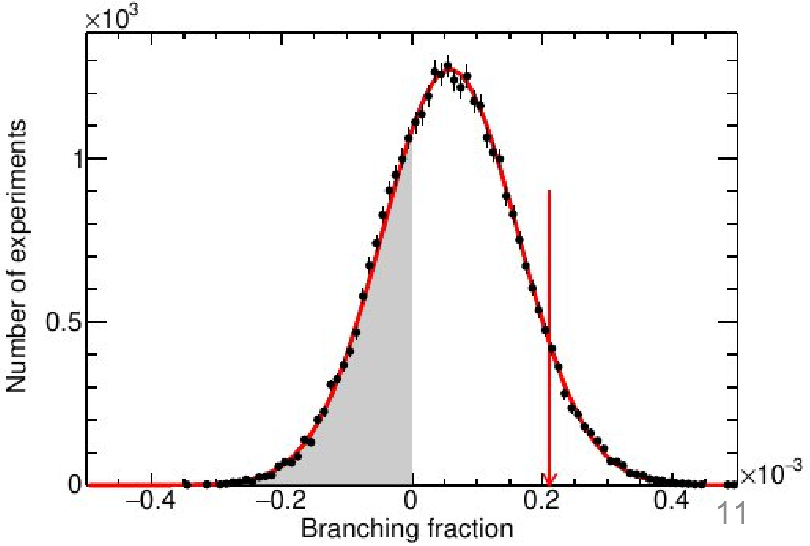


- First upper limit based on 2.93 fb^{-1} data @ 3.773 GeV:

$$B\left(D^0 \to \pi^0 \nu\bar{\nu}\right) < 2.1 \times 10^{-4} \text{ @ } 90\%\ CL$$

TABLE I. Summary of systematic uncertainties on the signal yield and detection efficiencies.

Source	Size
Number of π^0	4.0%
π^0 reconstruction	2.0%
Number of charged tracks	1.6%
$M^2_{\rm miss}$ requirement	0.7%
Signal model	0.5%
Wrong-tag background	1.7
$\pi^0 K^0_L X$ background shape	Negligible
Branching fraction of $\pi^0 \to \gamma\gamma$	Negligible



Search for $D_s^+ \to hh' e^+ e^-$

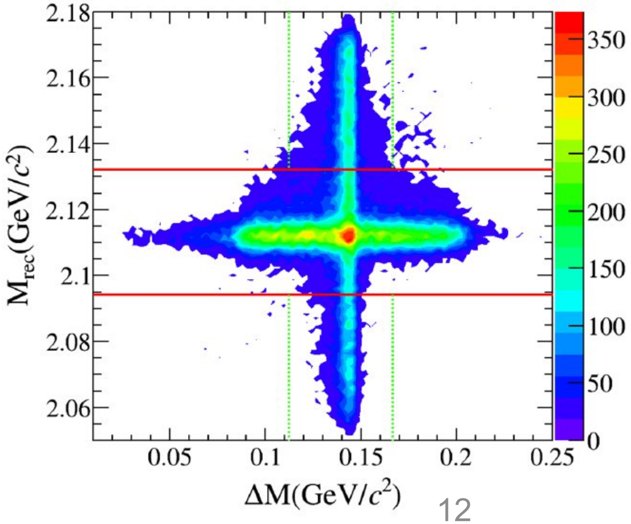
- First search for four-body FCNC processes of D_s^+
- Using 7.33 fb^{-1} data @ 4.128-4.226 GeV
- D_s^+ mainly from $e^+e^- \to D_s^{*\pm} D_s^{\mp}$, with total number of $N_{D_s^{\pm} D_s^{\mp}} = (64.7 \pm 0.3) \pm 10^5$
- Single-tag method, the BF for a given channel is given by:

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

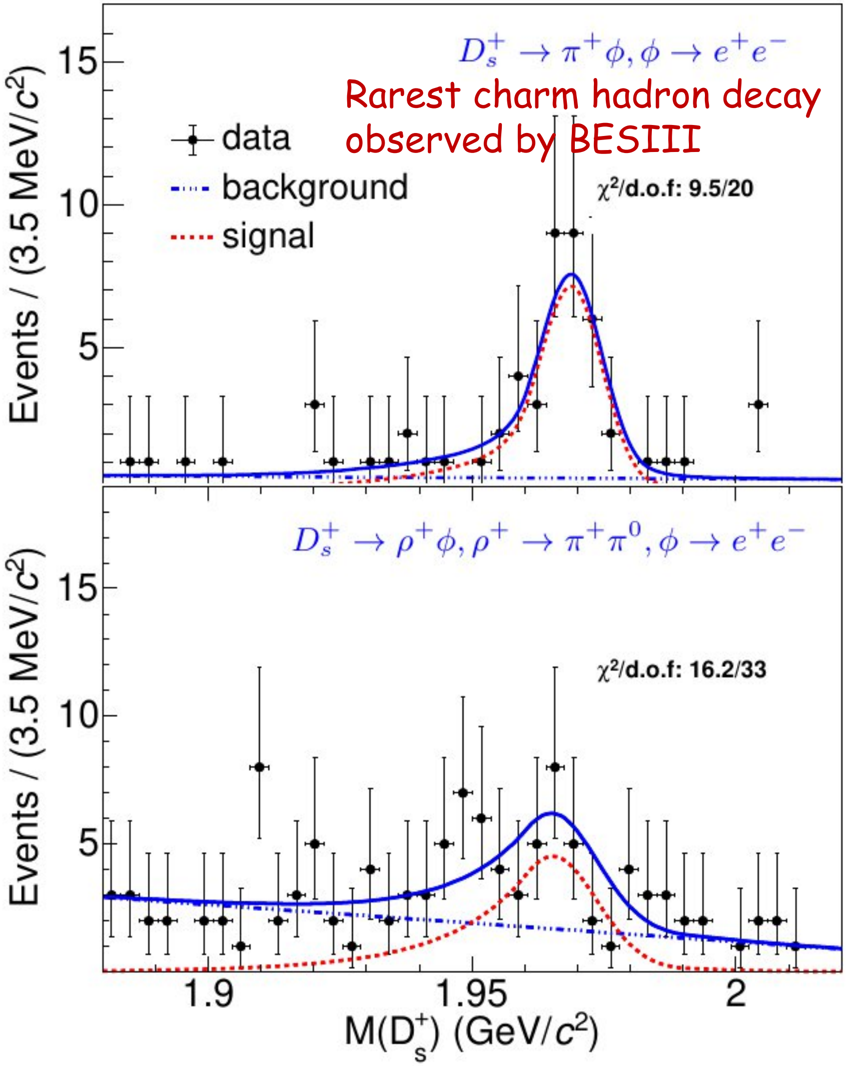
- 2D optimization of requirements on M_{rec} vs. ΔM

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

PRD 104, 012016 (2021)



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



- $M(e^+e^-) \in [0.98, 1.04]$ 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

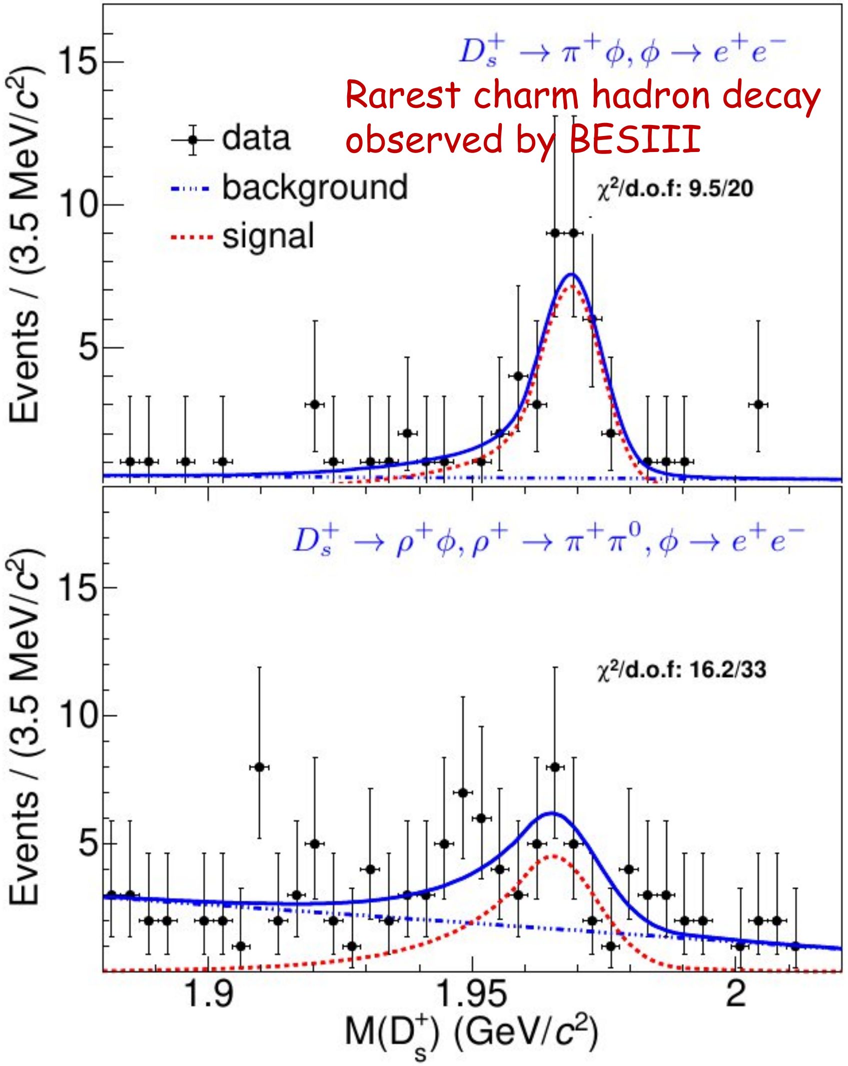
4.4σ for $D_s^+ \to \rho^+\phi$, $\phi \to e^+e^-$ — first evidence

NB: Using $D_{(s)}^+ \to \pi^+\phi$, LHCb measured

$$R_{\phi\pi} = 1.022 \pm 0.012\,(\text{stat}) \pm 0.048\,(\text{syst})$$

[JHEP 05 (2024) 293]

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



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[JHEP 05 (2024) 293]

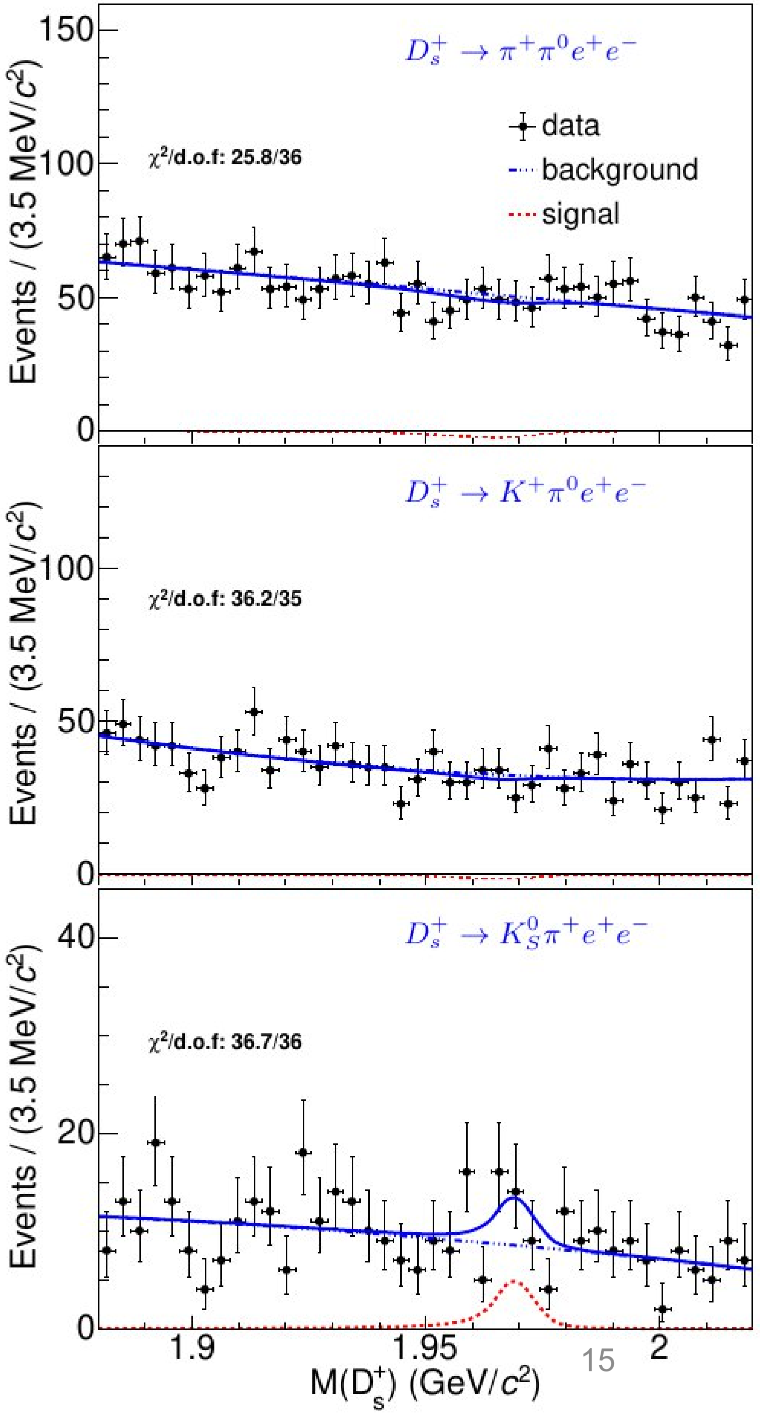
[arXiv:2404.05973]

Upper limits on $D_s^+ \to hh' e^+ e^-$

- Exclusion of events with $M(e^+e^-) \in [0.96, 1.05]$ GeV for mode $\pi^+\pi^0 e^+e^-$
- Likelihood scan to determine upper limits @ 90% CL:

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

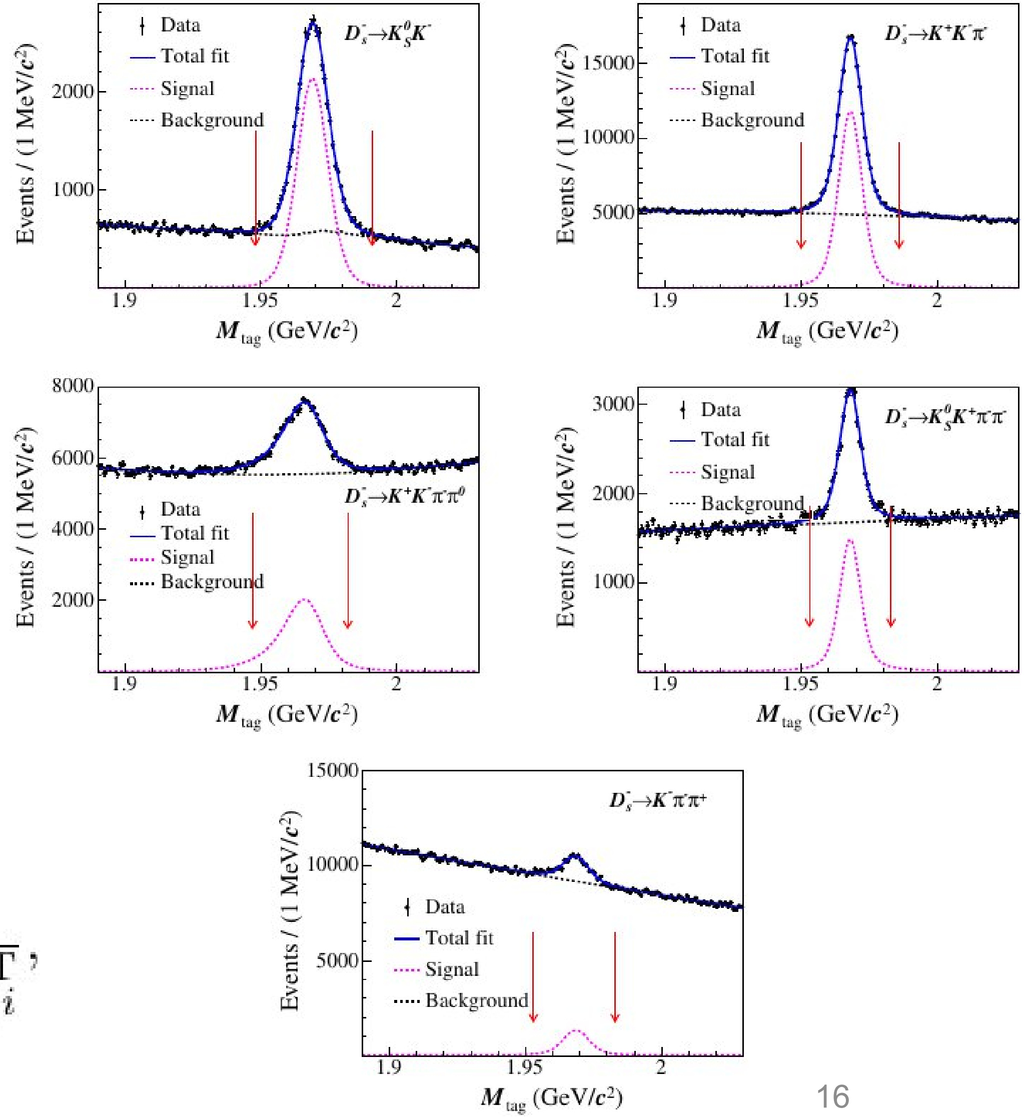
All first upper limits!



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

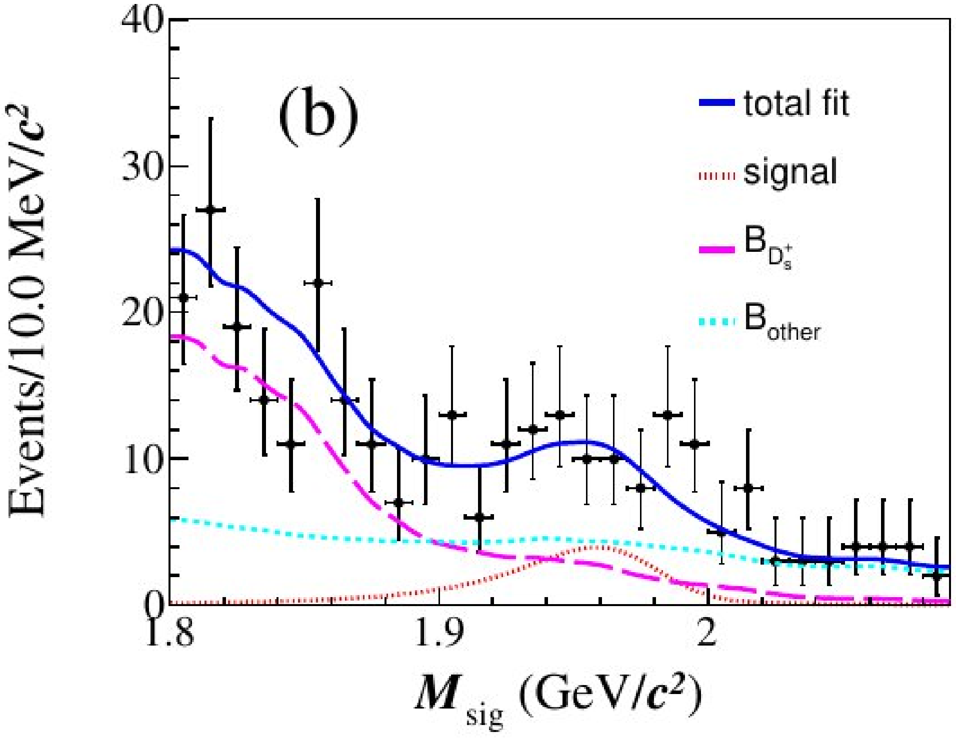
- First search for a radiative D_s^+ decay
- BF important to test QCD-based LD calculations & predictions of CPV in D decays
- 7.33 fb^{-1} data @ $E_{cm} \in [4.128, 4.226]$ GeV
- Double-tag method with five modes

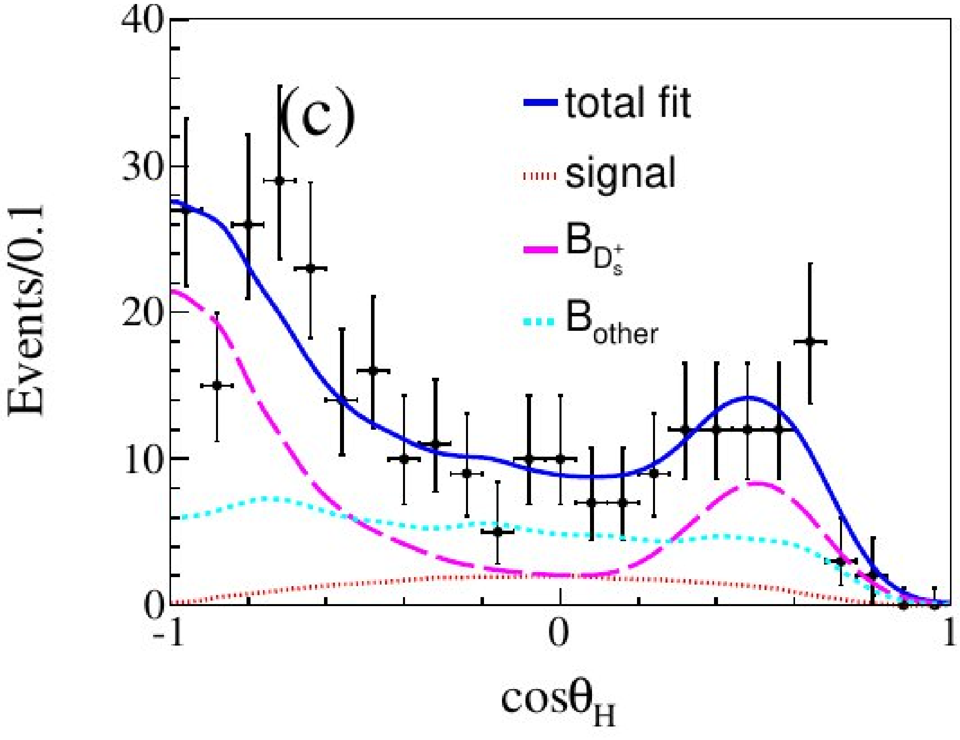
$$\mathcal{B}(D_s^+ \to \gamma\rho(770)^+) = \frac{N_{\rm total}^{\rm DT}}{B(\pi^0 \to \gamma\gamma)\sum_{\alpha,i} N_{\alpha,i}^{\rm ST}\epsilon_{\alpha,i}^{\rm DT}/\epsilon_{\alpha,i}^{\rm ST}},$$



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

- 2D fit to extract signal yield N_{DT} = 33 ± 14 with statistical significance of 2.5σ



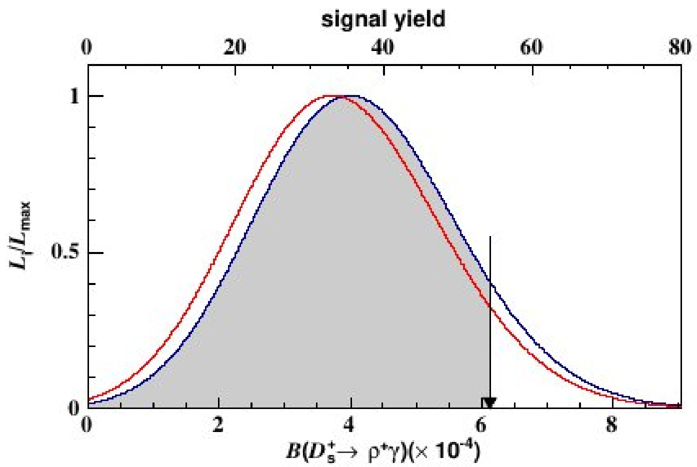


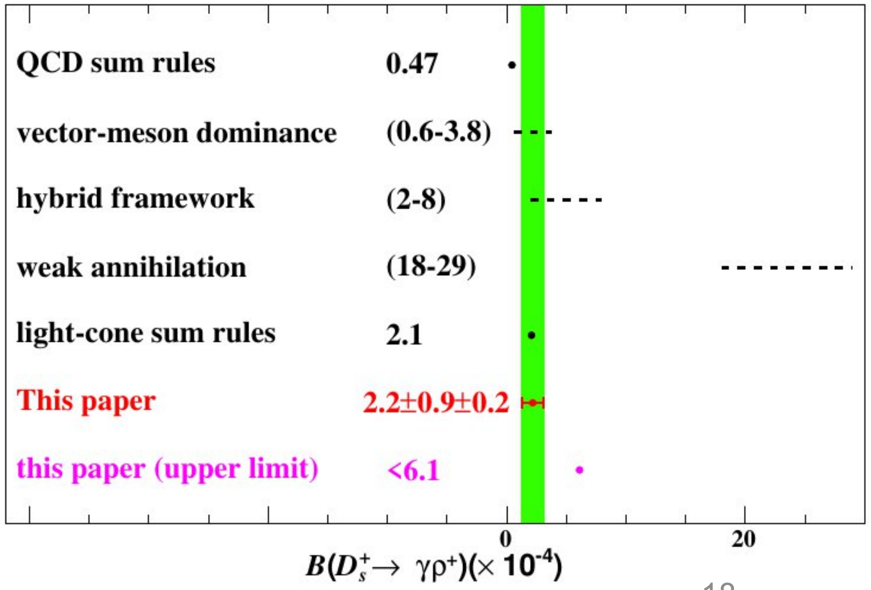
Search for $D_s^+ \to \gamma\rho(770)^+$

- 2D fit to extract signal yield N_{DT} = 33 ± 14 with statistical significance of 2.5σ
- The BF is measured to be

$$B\left(D_s^+ \to \gamma\rho(770)^+\right) = (2.2 \pm 0.9 \pm 0.2) \times 10^{-4},$$

with UL set at $< 6.1 \times 10^{-4}$ @ 90% CL

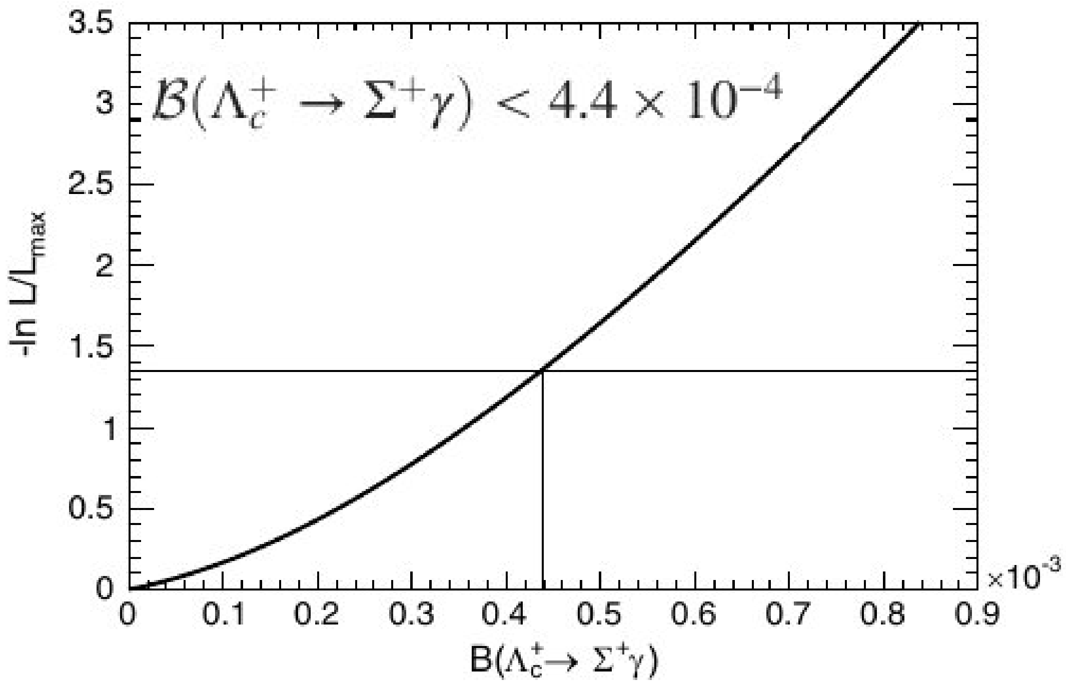




Other related BESIII results

Decay channel	Dataset	Ref.
$D \to h(h^{(\prime)})e^+e^-$	2.93 fb^{-1} @ 3.773 GeV	PRD 97 (2018) 072015
$\Lambda_c^+ \to \Sigma^+\gamma$	4.5 fb^{-1} @ 4.60 -- 4.70 GeV	PRD 107 (2022) 052002

Signal decays	$\mathcal{B}$ $(\times 10^{-5})$
$D^+ \to \pi^+\pi^0 e^+e^-$	<1.4
$D^+ \to K^+\pi^0 e^+e^-$	<1.5
$D^+ \to K_S^0\pi^+ e^+e^-$	<2.6
$D^+ \to K_S^0 K^+ e^+e^-$	<1.1
$D^0 \to K^-K^+ e^+e^-$	<1.1
$D^0 \to \pi^+\pi^- e^+e^-$	<0.7
$D^0 \to K^-\pi^+ e^+e^{-\dagger}$	<4.1
$D^0 \to \pi^0 e^+e^-$	<0.4
$D^0 \to \eta e^+e^-$	<0.3
$D^0 \to \omega e^+e^-$	<0.6
$D^0 \to K_S^0 e^+e^-$	<1.2
† in $M_{e^+e^-}$ regions:	
$[0.00, 0.20)$ GeV/c^2	<3.0 $(1.5^{+1.0}_{-0.9})$
$[0.20, 0.65)$ GeV/c^2	<0.7
$[0.65, 0.90)$ GeV/c^2	<1.9 $(1.0^{+0.5}_{-0.4})$



White Paper
CPC 44 (2020) 040001

Prospects

10^{-6} 10^{-6}

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		0.5
$D^0 \to \pi^+ \pi^- e^+ e^-$	0.7	BESIII	2018		0.3
$D^0 \to K^+ K^- e^+ e^-$	1.1	BESIII	2018		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	201		70.0
$D_s^+ \to K^+ e^+ e^-$	3.7	BaBar	2011		1.7

20 fb^{-1}
@ 3.773 GeV

6 fb^{-1}@ 4.18 GeV

Summary

- Rare D decays related to $c \to u$ processes offer unique opportunities for indirect NP searches
- With world's largest data samples near charm thresholds, and superb detector performance, BESIII has great potentials to make significant impacts in the field
- A lot of analyses still in the pipeline, stay tuned!
  - Updated searches on $D \to h(h^{(\prime)})e^+e^-$
  - Radiative $D_{(s)}$ decays
  - Invisible ($D_{(s)} \to X\nu\bar{\nu}$) decays