Experimental status of ~~Rare~~ charm decays

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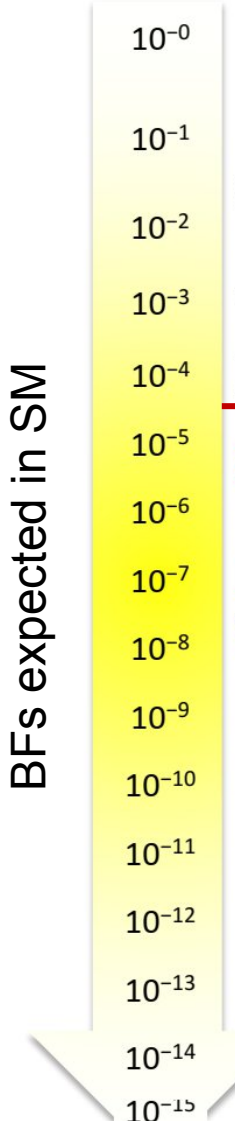
Outline

- Overview of rare charm decays
- Recent results on searches of:
  - $\Lambda_c^+ \to \Sigma^+ \gamma$ and $\Xi_c^0 \to \Xi^0 \gamma$
  - $\Lambda_c^+ \to p \gamma'$
  - $D^0 \to \mu^+ \mu^-$
  - $D^{*0} \to \mu^+ \mu^-$
  - $D^+ \to n(\bar{n}) e^+$
- Prospects
- Summary

Summary of charm decays



Charm offers 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

Cabibbo favor

Single Cabibbo suppressed

Doubly Cabibbo suppressed

Radiative decays

$D^0 \to K^{*0}\gamma/\phi\gamma/\omega\gamma/\rho\gamma$

$D^+_{(s)} \to K^{*+}\gamma/\rho^+\gamma$

Long distance:
Vector meson Dominance (SM)

$D^{0+} \to \gamma\gamma/VV'(l^+l^-)/\ hV(l^+l^-)/\ hh'V(l^+l^-)$

Rare decays

Short distance FCNC (SM+NP)

$D^{0/+} \to \gamma\gamma/Vl^+l^-/hl^+l^-/hh'l^+l^-$

$D^0 \to \mu^+\mu^-/e^+e^-$

$D \to (hh)\mu^+\mu^+/(hh)e^+e^+$

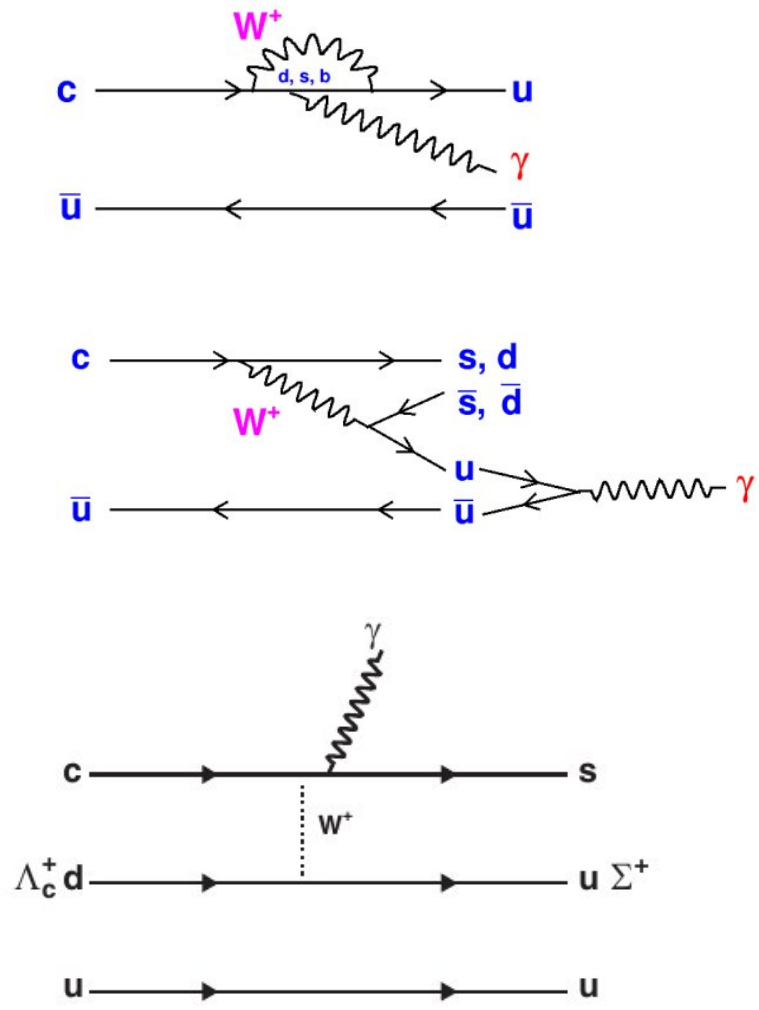
$D \to (h)\mu^+e^-$

$D \to (h)pe^-$

(NP)
Forbidden decays: LNV, LFV, BNV

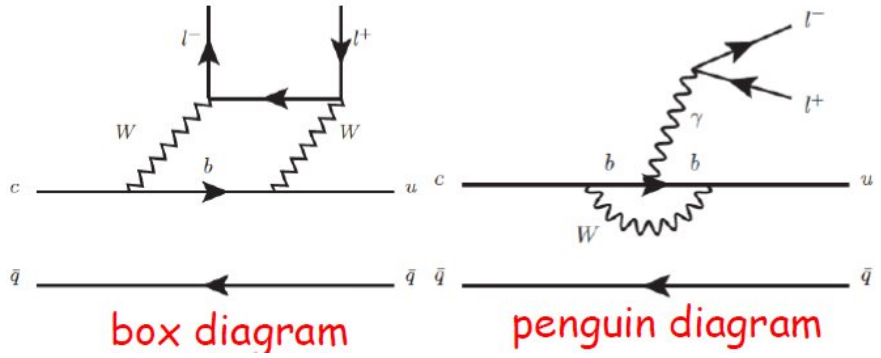
Weak radiative decays

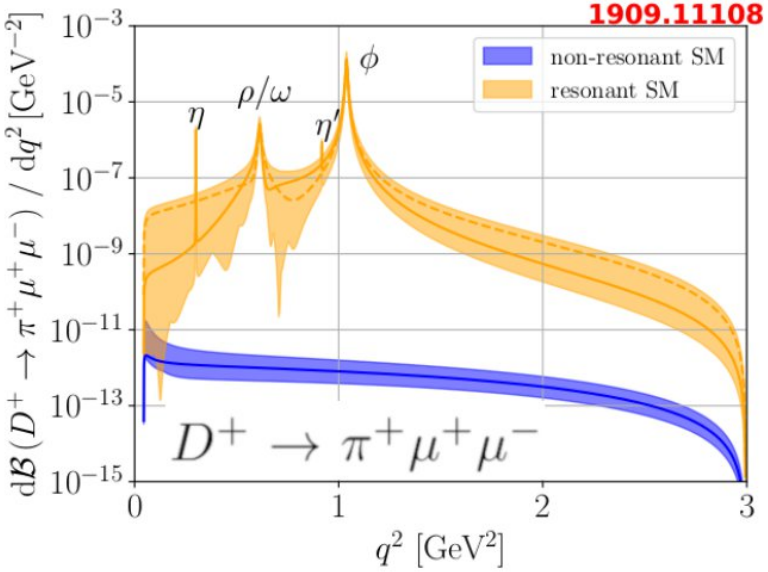
- Short-Distance contribution from EM penguin highly suppressed
- Dominated by Long-Distance contributions, putting expected BFs up to 10^{-4}
- Already observed decays with BF ~10^{-5}—10^{-4}
  - $D^0 \to \phi\gamma$, $D^0 \to \rho^0\gamma$, and $D^0 \to \overline{K}^*(892)^0\gamma$
- A test for QCD based calculations for LD effects
- First weak radiative decay of a bottom baryon, $\Lambda_b^0 \to \Lambda^0\gamma$ already observed in 2019 [LHCb, PRL 123, 031801 (2019)]
- No such measurement existed for charmed baryons by mid 2022

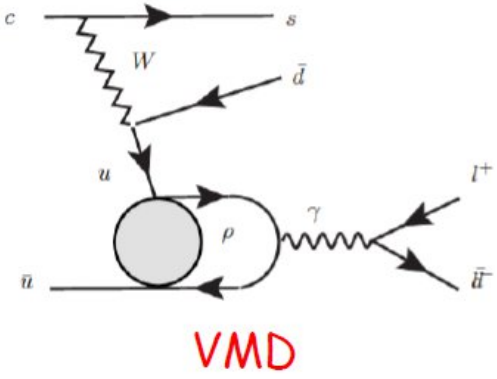


Flavor **C**hanging **N**eutral **C**urrents

- Forbidden at tree level in SM, only allowed in loop and box diagrams
  - Strongly suppressed due to GIM cancellation:
  - BF ~$\mathcal{O}(10^{-9})$
- $D \to X\ell^+\ell^-$ dominated by Long-Distance contributions
  - Vector Meson dominance (VMD)
  - BF ~$\mathcal{O}(10^{-6})$

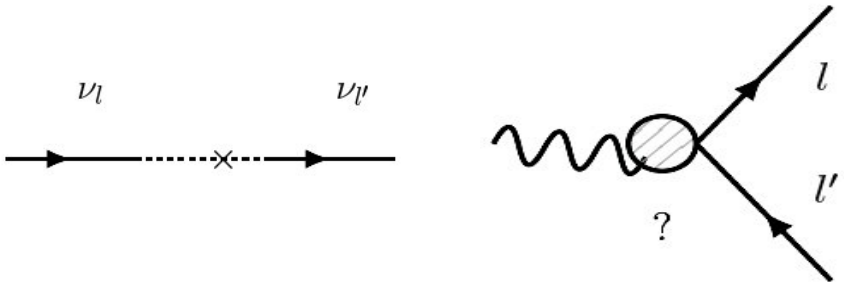


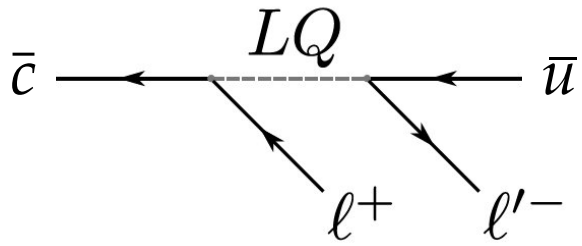




Lepton **F**lavor **V**iolation

- LFV exists in neutrino oscillation
- Observation of charged LFV (cLFV) decays will be a clear sign for NP
- Lepton flavor non-universality closely related to cLFV
  - See, *e.g.* the talk by S. Schmitt on Tuesday
- BSM models (lepto-quark, Z', etc.) may induce cLFV and enhance BF up to $\mathcal{O}(10^{-5})$



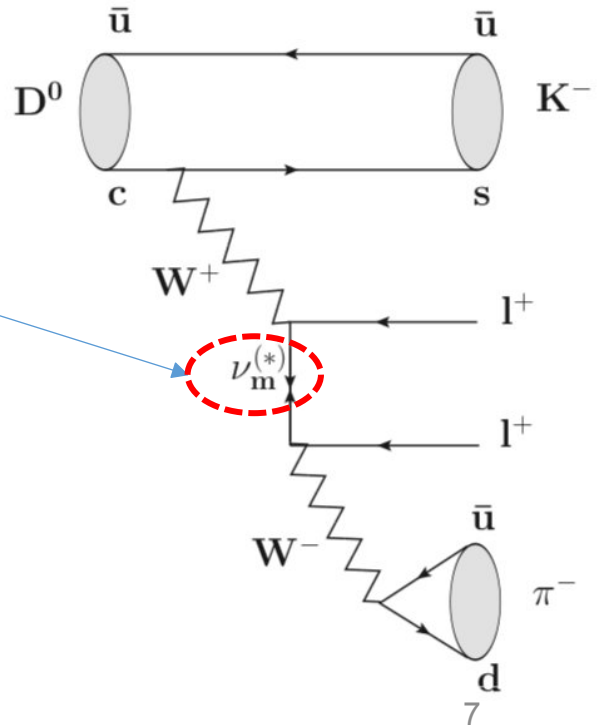


Lepton Number Violation

- **L**epton **N**umber **V**iolation ($\Delta L \neq 0$) is forbidden in SM
- Neutrino oscillation $\rightarrow m_\nu \neq 0 \rightarrow$ New Physics needed to explain mass origin
- Nature of neutrino: Dirac or Majorana (ν_{m})?
- 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, etc.
- LNV processes have been widely searched for in τ, K, D, and B decays

$$\begin{pmatrix} \nu_\uparrow \\ \nu_\downarrow \\ \bar{\nu}_\uparrow \\ \bar{\nu}_\downarrow \end{pmatrix} \quad \text{or} \quad \begin{pmatrix} \nu_\uparrow \\ \nu_\downarrow \end{pmatrix}$$

Dirac Majorana

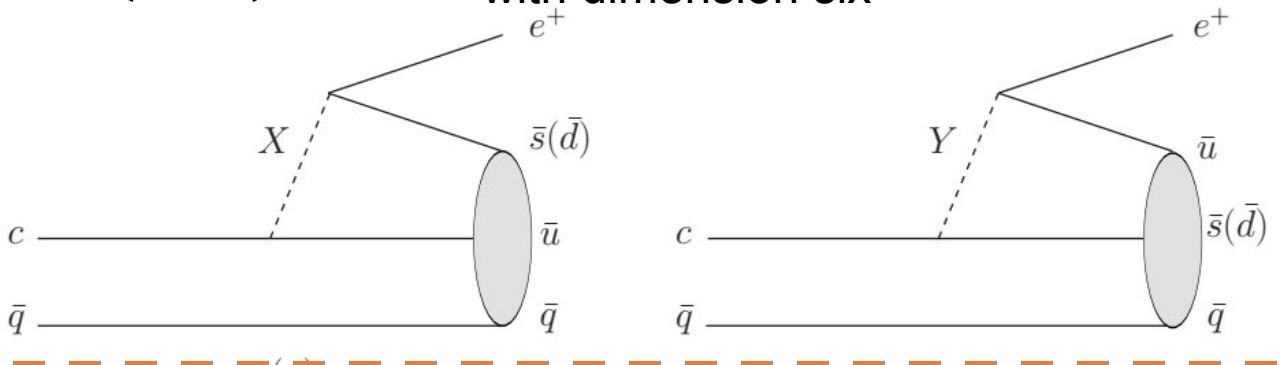


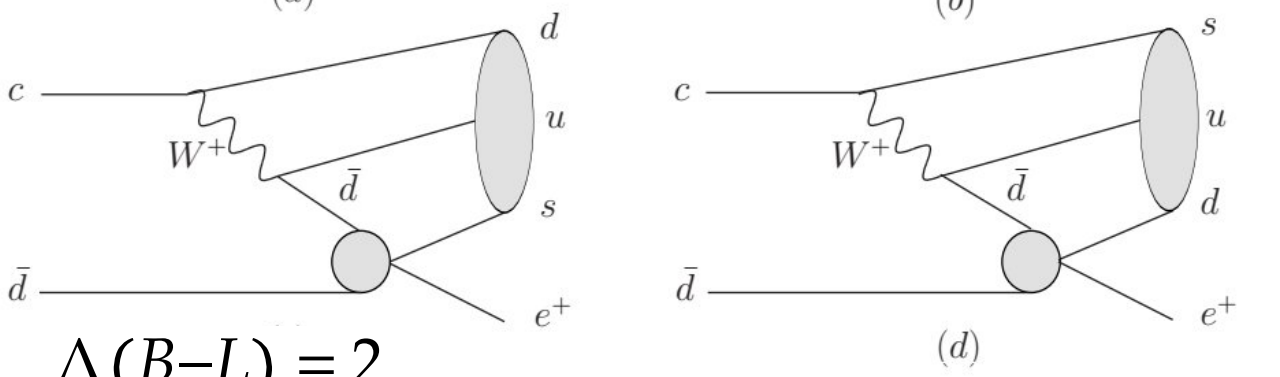
Baryon **N**umber **V**iolation

- Excess of baryons over antibaryons in the Universe → BNV processes exist
- BNV is allowed in GUTs and some SM extensions
  - Accompanied by LNV
- BFs of $D \to B\ell$, $B = \Lambda,\Sigma,\mathrm{p},\mathrm{n}$ expected to be no more than $O(10^{-29})$ [PRD 72, 095001 (2005)]

$\Delta(B-L) = 0$

Feynman diagrams under operators with dimension six



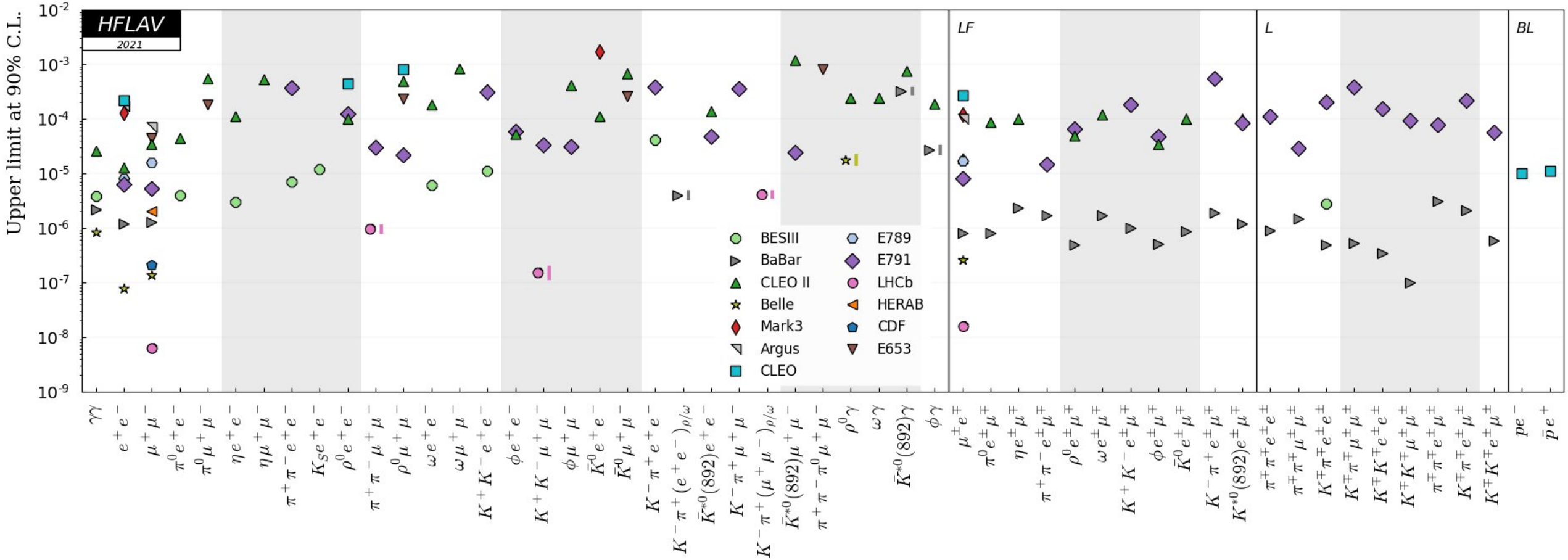


$\Delta(B-L) = 2$

Feynman diagrams under operators with dimension seven

Results on rare charm decays (D^0)

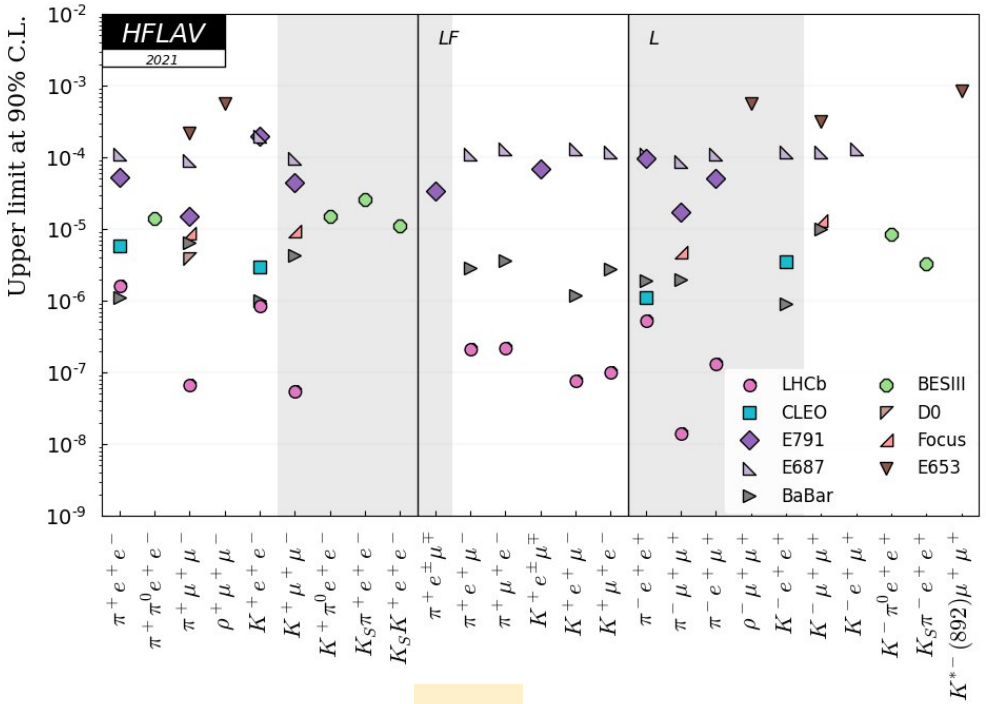
By Spring 2021



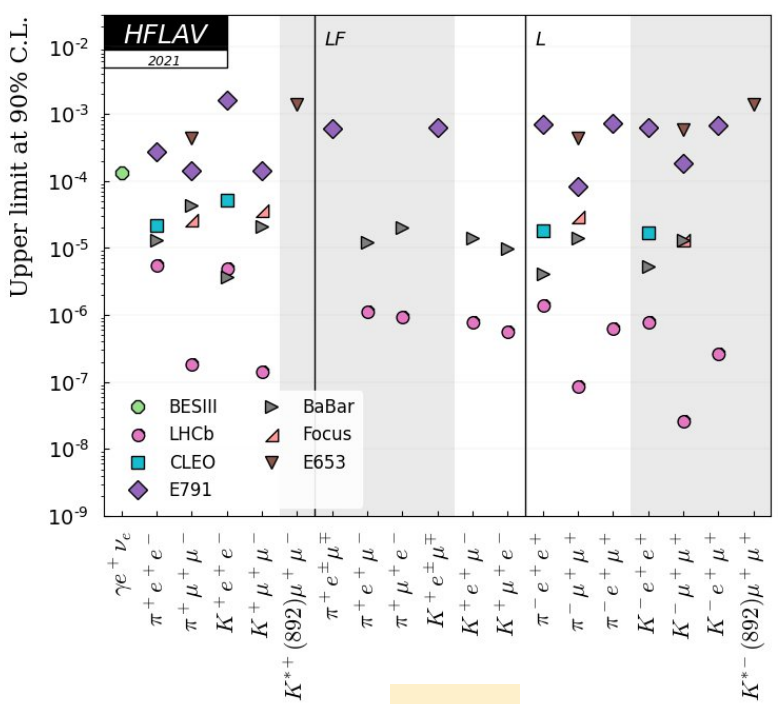
https://hflav-eos.web.cern.ch/hflav-eos/charm/rare/Spring2021/rare_charm.html

Results on rare charm decays ($D^+_{(s)}$, Λ_c^+)

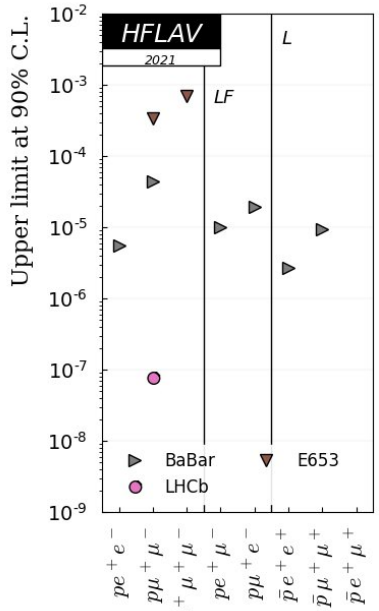
By Spring 2021



D^+



D_s^+

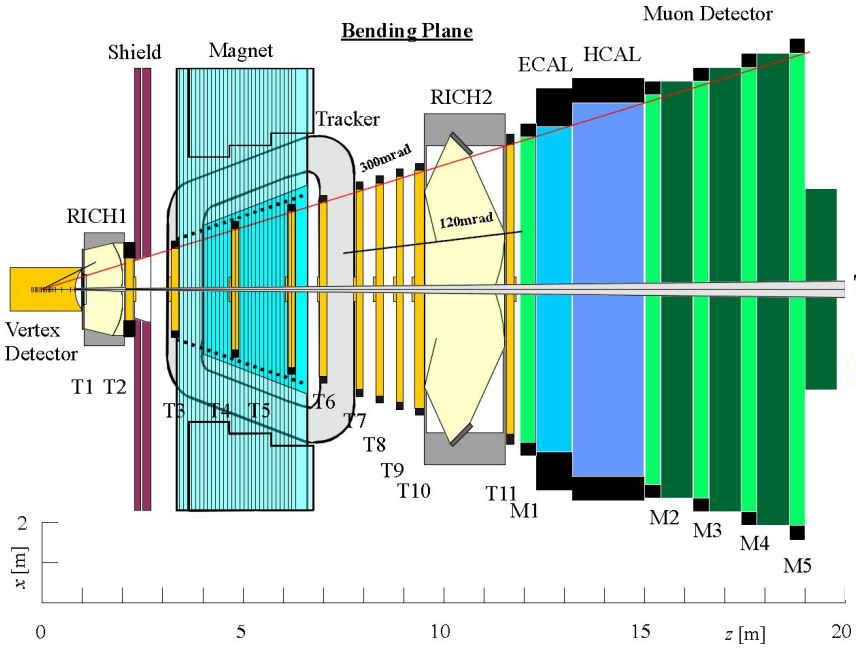


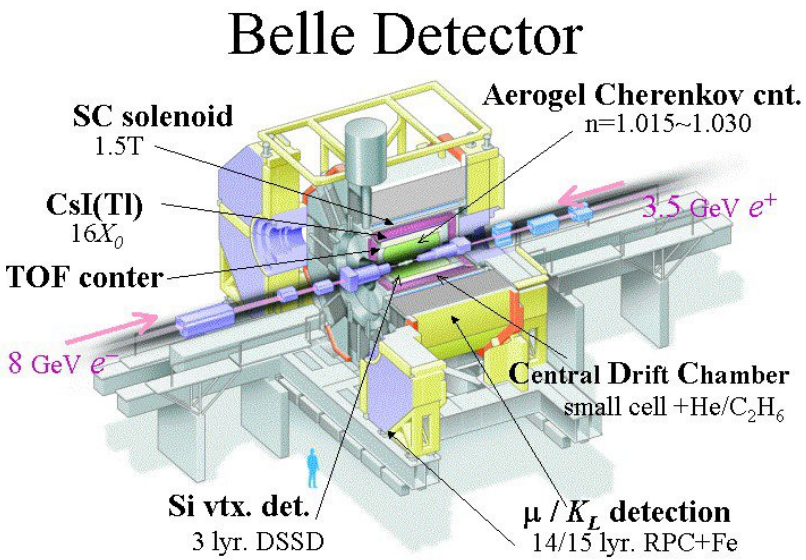
Λ_c^+

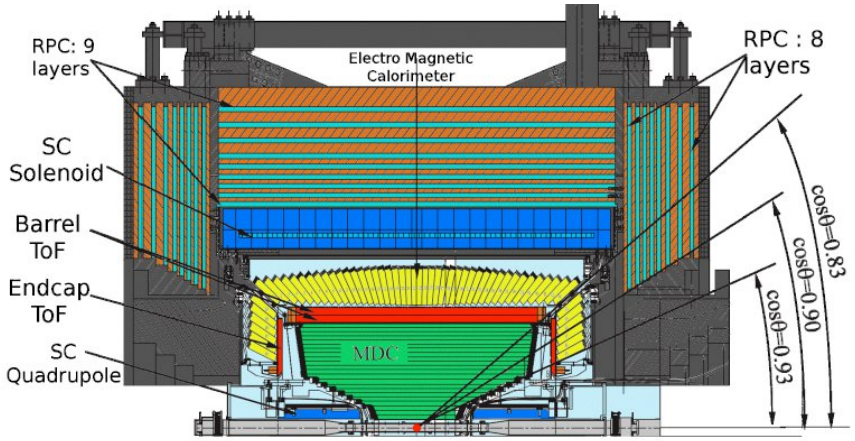
Still a lot of unexplored decay channels

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

Major experiments for charm physics







PRD 105 (2022) L071102
PRD 105 (2022) 032006

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

- Both using 2.93 fb^{-1} ψ(3770) data
- First search of D decaying into $\nu\bar{\nu}$ final state yields:

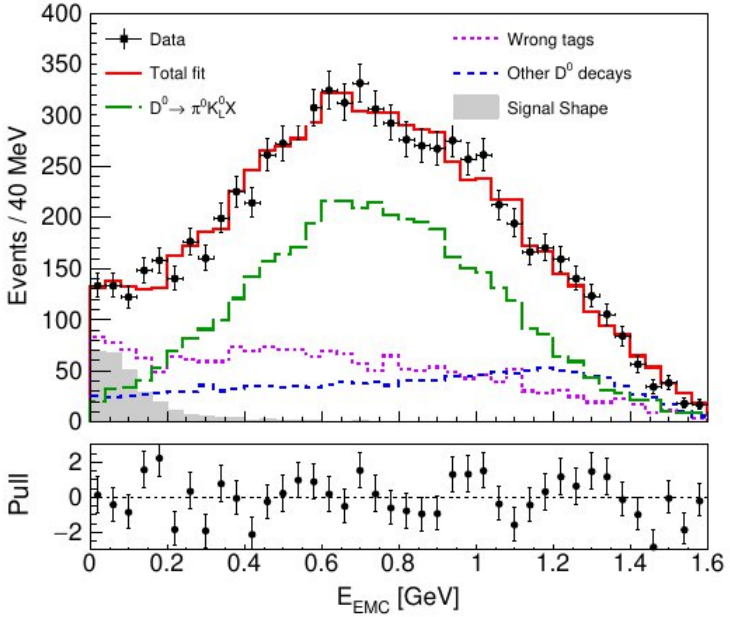
$$B\left(D^0 \to \pi^0 \nu\bar{\nu}\right) < 2.1 \times 10^{-4} \text{ @ } 90\% \; CL$$

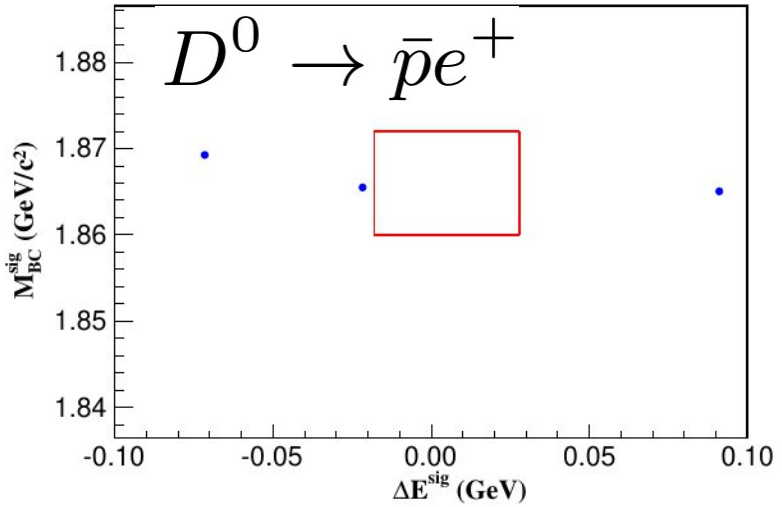
- With flavor of D determined from tag side, upper limits @ 90% CL are set:

$$\mathcal{B}_{D^0 \to \bar{p}e^+} < 1.2 \times 10^{-6}$$

$$\mathcal{B}_{D^0 \to pe^-} < 2.2 \times 10^{-6}$$

Both results already presented during FPCP2022

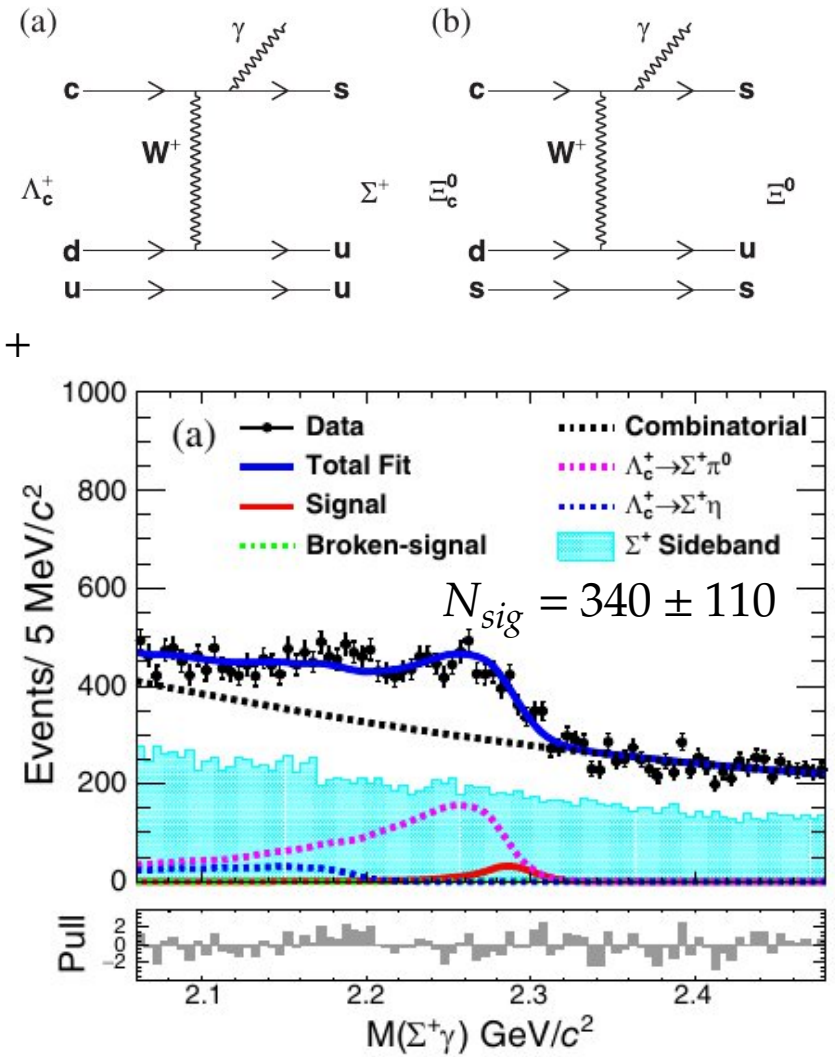




$\Lambda_c^+ \to \Sigma^+\gamma$ and $\Xi_c^0 \to \Xi^0\gamma$

- Using 980 fb^{-1} data collected at or near $\Upsilon(\mathrm{nS})$
- Using normalization channels $\Lambda_c^+ \to pK^-\pi^+$ and $\Xi_c^0 \to \Xi^-\pi^+$
- Requiring $\Sigma^+ \to p\pi^0$, $\Xi^{0,-} \to \Lambda(\to p\pi^-)\pi^{0,-}$
- Isolated photon with $E(\gamma) > 0.65\ (0.8)$ GeV in the barrel (endcap) of ECL
- The peaking backgrounds of $\Lambda_c^0 \to \Sigma^0\pi^0(\eta)$ are estimated from simulation and BFs from PDG
- No evidences for signals found, upper limits @ 90% CL are set:

$$\mathcal{B}(\Lambda_c^+ \to \Sigma^+\gamma) < 2.6 \times 10^{-4}$$
$$\mathcal{B}(\Xi_c^0 \to \Xi^0\gamma) < 1.8 \times 10^{-4}$$

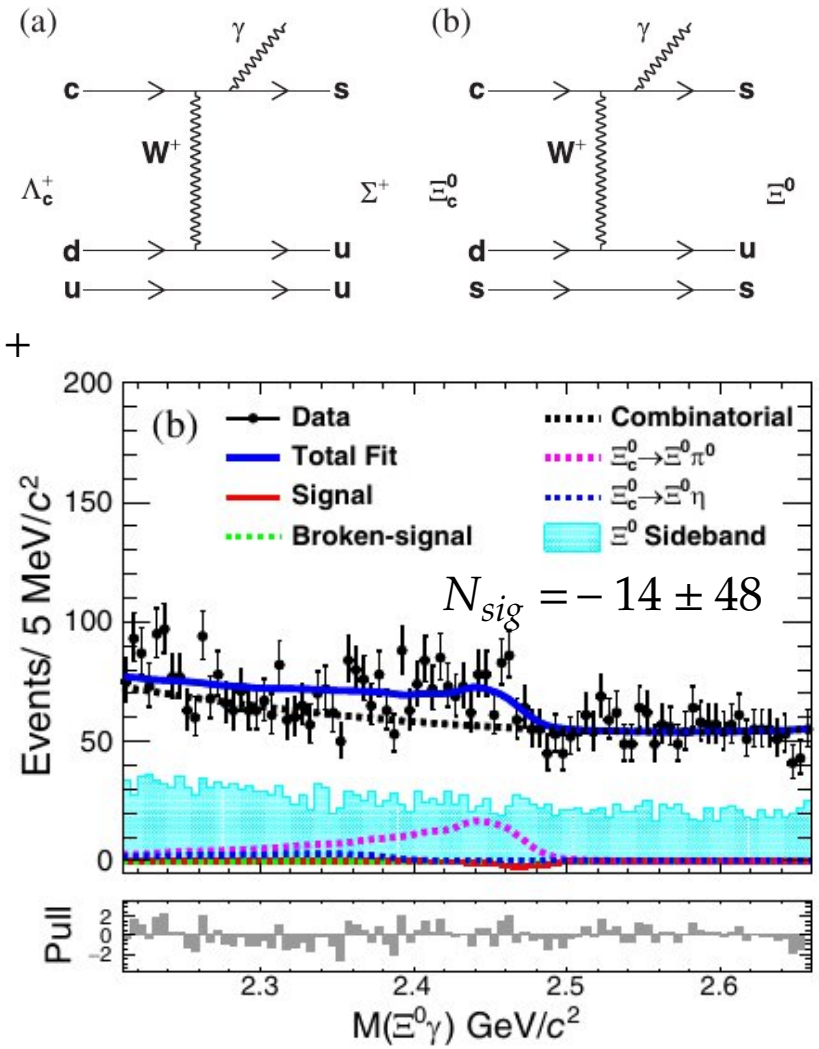


First searches of weak radiative decays of charm baryons

$\Lambda_c^+ \to \Sigma^+ \gamma$ and $\Xi_c^0 \to \Xi^0 \gamma$

- Using 980 fb^{-1} data collected at or near $\Upsilon(\mathrm{nS})$
- Using normalization channels $\Lambda_c^+ \to pK^-\pi^+$ and $\Xi_c^0 \to \Xi^-\pi^+$
- Requiring $\Sigma^+ \to p\pi^0$, $\Xi^{0,-} \to \Lambda(\to p\pi^-)\pi^{0,-}$
- Isolated photon with $E(\gamma) > 0.65\ (0.8)$ GeV in the barrel (endcap) of ECL
- The peaking backgrounds of $\Xi_c^0 \to \Xi^0\pi^0(\eta)$ are estimated based on dedicated data samples
- No evidences for signals found, upper limits @ 90% CL are set:

$$\mathcal{B}(\Lambda_c^+ \to \Sigma^+\gamma) < 2.6 \times 10^{-4}$$
$$\mathcal{B}(\Xi_c^0 \to \Xi^0\gamma) < 1.8 \times 10^{-4}$$



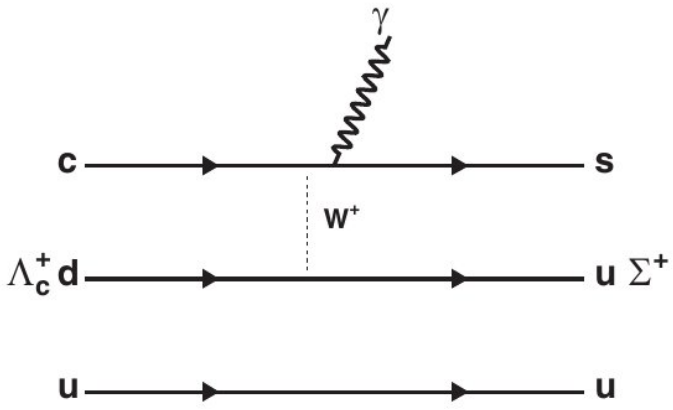
First searches of weak radiative decays of charm baryons

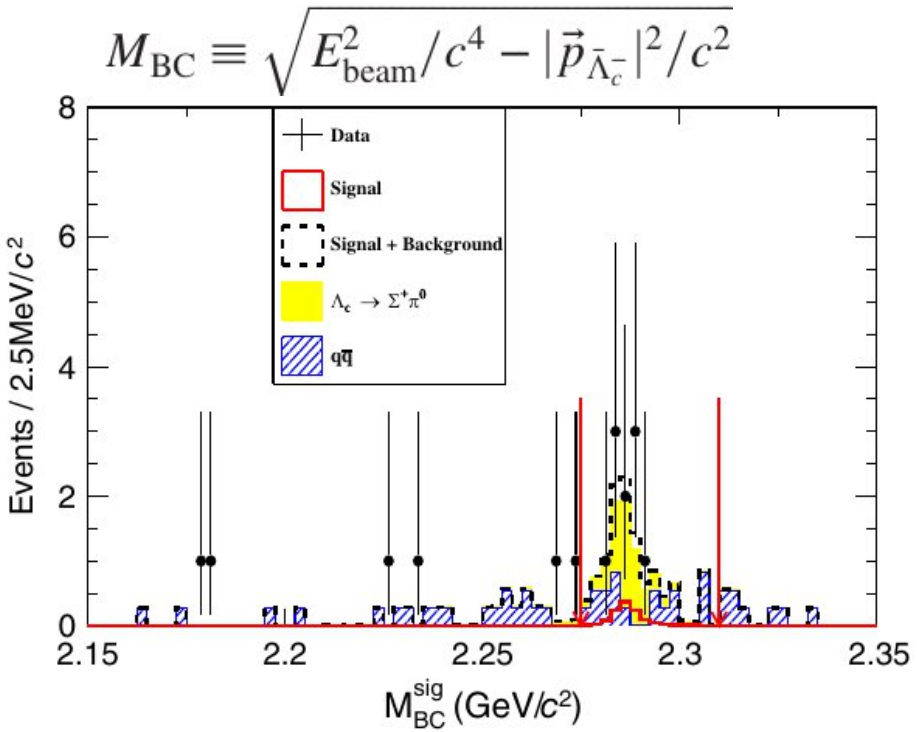
PRD 107 (2023) 052002

$\Lambda_c^+ \to \Sigma^+ \gamma$

- Using 4.5 fb^{-1} e^+e^- data at seven energy points between $\sqrt{s} = 4.600 - 4.699$ GeV
- Fully reconstruct a $\overline{\Lambda}_c^-$ at tag (ST) side
- Requiring $\Sigma^+ \to p\pi^0$
- Isolated photon with $E(\gamma) > 0.6$ GeV
- Background contributions estimated from simulation & known $\Lambda_c^+ \to \Sigma^+ \pi^0$ BF
- No significant signal found, upper limit @ 90% CL is set:

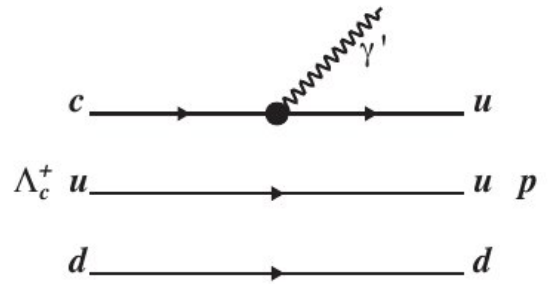
$$\mathcal{B}(\Lambda_c^+ \to \Sigma^+ \gamma) < 4.4 \times 10^{-4}$$





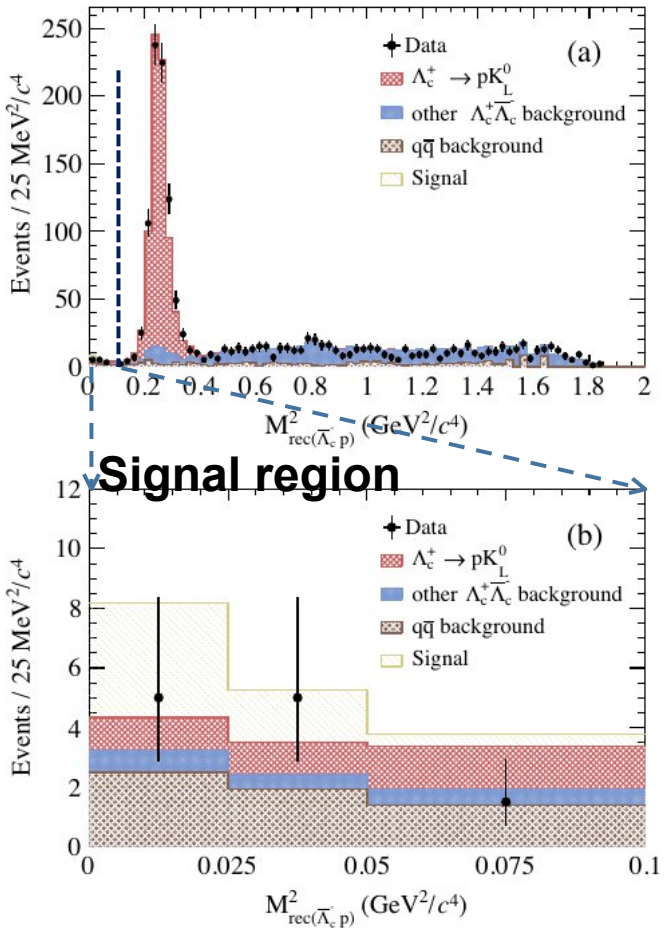
PRD 106 (2022) 072008

$\Lambda_c^+ \to p\gamma'$



- FCNC process of $c \to u$ with the emission of a massless dark photon expected in some BSM models with BF up to 10^{-5} [PRD 102 (2020) 115029]
- Using 4.5 fb^{-1} e^+e^- data at seven energy points between $\sqrt{s} = 4.600 - 4.699$ GeV
- Fully reconstruct a $\overline{\Lambda}_c^-$ at tag (ST) side
- The γ' signal is reconstructed from the recoil mass against $\overline{\Lambda}_c^-$ and p (missing part)
- Background contributions estimated from simulation & known $\Lambda_c^+ \to pK_L^0$ BF
- The decay BF is determined from $\mathcal{B}(\Lambda_c^+ \to p\gamma') = \frac{N_{\rm obs} - N_{\rm bkg}}{\sum_{ij} N_{ij}^{\rm ST} \cdot (\epsilon_{ij}^{\rm DT}/\epsilon_{ij}^{\rm ST})}$
- No significant signal found, upper limit is set:

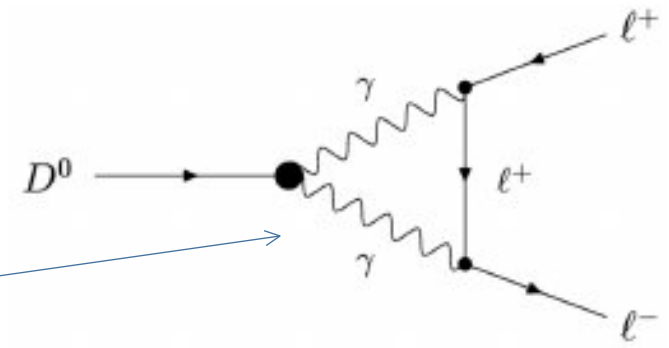
$$\mathcal{B}(\Lambda_c^+ \to p\gamma') < 8.0 \times 10^{-5} \quad \text{at} \quad 90\% \quad \text{C.L.}$$



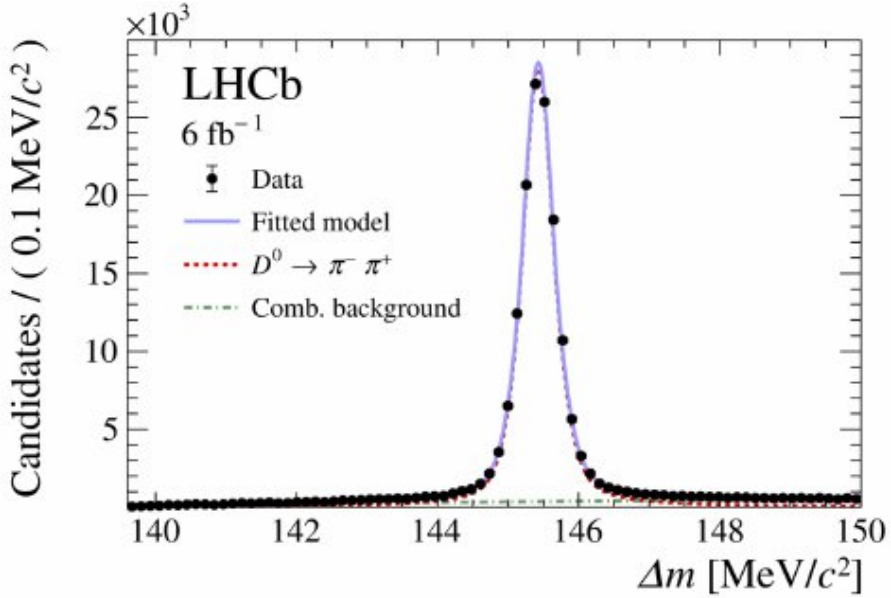
First search in the charmed baryon sector!

arXiv:2212.11203

Search for $D^0 \to \mu^+\mu^-$



- Short-distance contribution from $c \to u\ell\ell$ (FCNC) highly suppressed: Br~10^{-18}
- Long-distance from a two-photon intermediate state: Br < 10^{-13}
- Dataset: full Runs1+2 9 fb^{-1}
- D^0 candidates from $D^{*+} \to D^0\pi^+$
- Normalization channels: $D^0 \to K^-\pi^+, \pi^+\pi^-$
- BDT trained to suppress combinatorial backgrounds



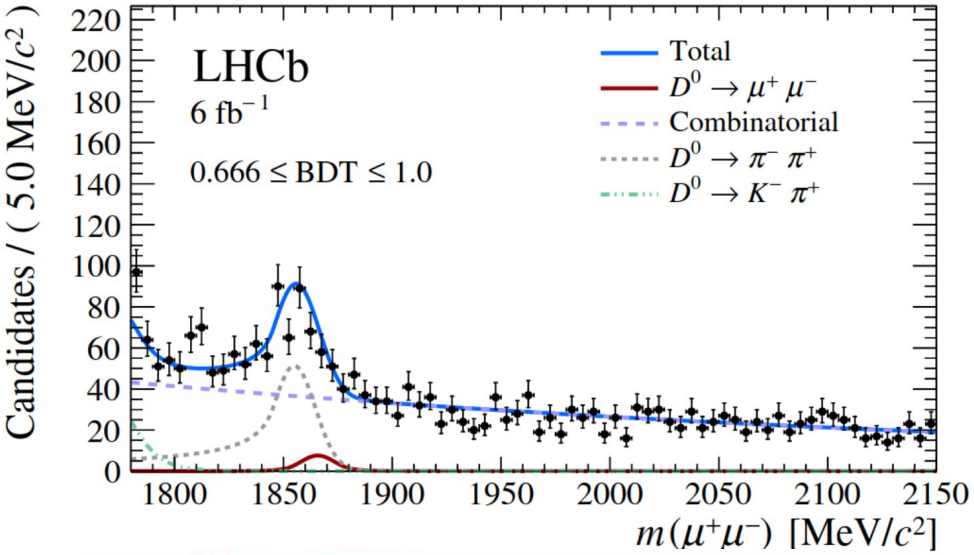
arXiv:2212.11203

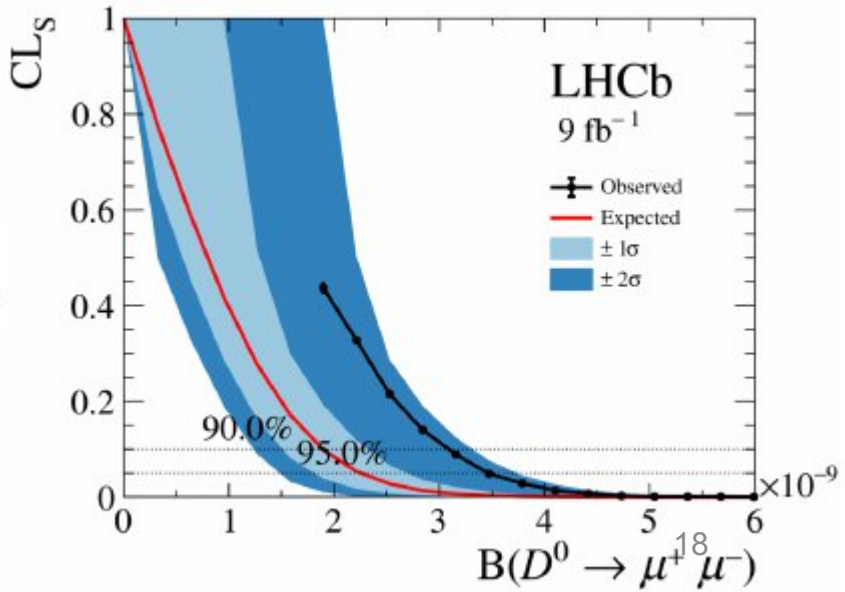
Search for $D^0 \to \mu^+\mu^-$: results

- Peaking backgrounds from $D^0 \to h\pi$ are carefully calibrated using MC & control samples
  - $K\pi$: $\mu\mu$ mass sideband
  - $\pi\pi$: $D^+_{(s)} \to \pi\pi\pi$ decays
- Final yield: $N\left(D^0 \to \mu\mu\right) = 79 \pm 45$
- Upper limits are set:

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

A factor of 2 improvement!





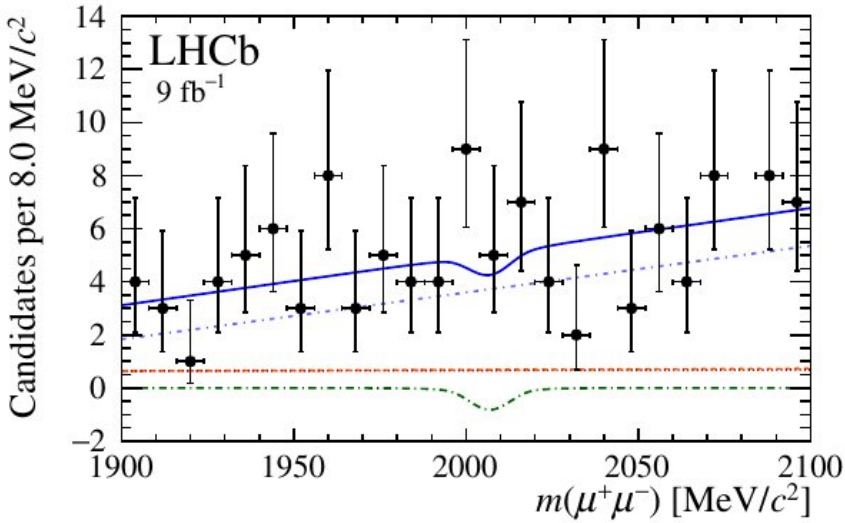
arXiv:2304.01981

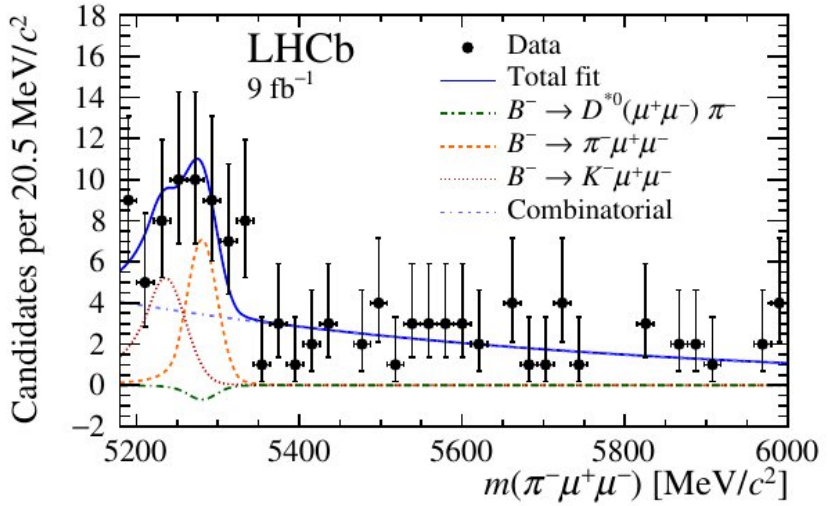
Search for $D^{*0} \to \mu^+\mu^-$ in B decay

- Leptonic D^* decays offer a complementary approach to constraining Wilson coefficients
- Highly suppressed in SM: BF ~10^{-18}
- Search in the decay chain of $B^- \to D^{*0}(\to \mu^+\mu^-)\pi^-$
- Normalization channel: $B^- \to J/\psi(\to \mu^+\mu^-)K^-$
- First search:

$$\varepsilon_{J/\psi K^-}/\varepsilon_{D^{*0}\pi^-} \quad 1.21 \pm 0.03$$
$$N_{J/\psi K^-} \quad (2316 \pm 8) \times 10^3$$

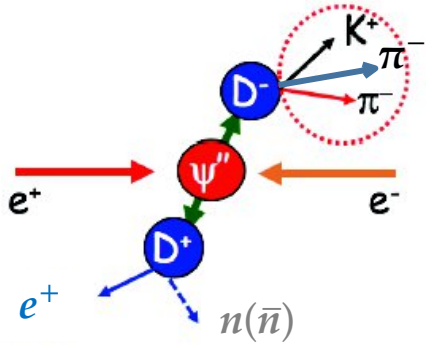
$$\mathcal{B}(D^{*0} \to \mu^+\mu^-) < 2.6 \times 10^{-8} \text{ at } 90\% \text{ CL}$$





PRD 106 (2022) 112009

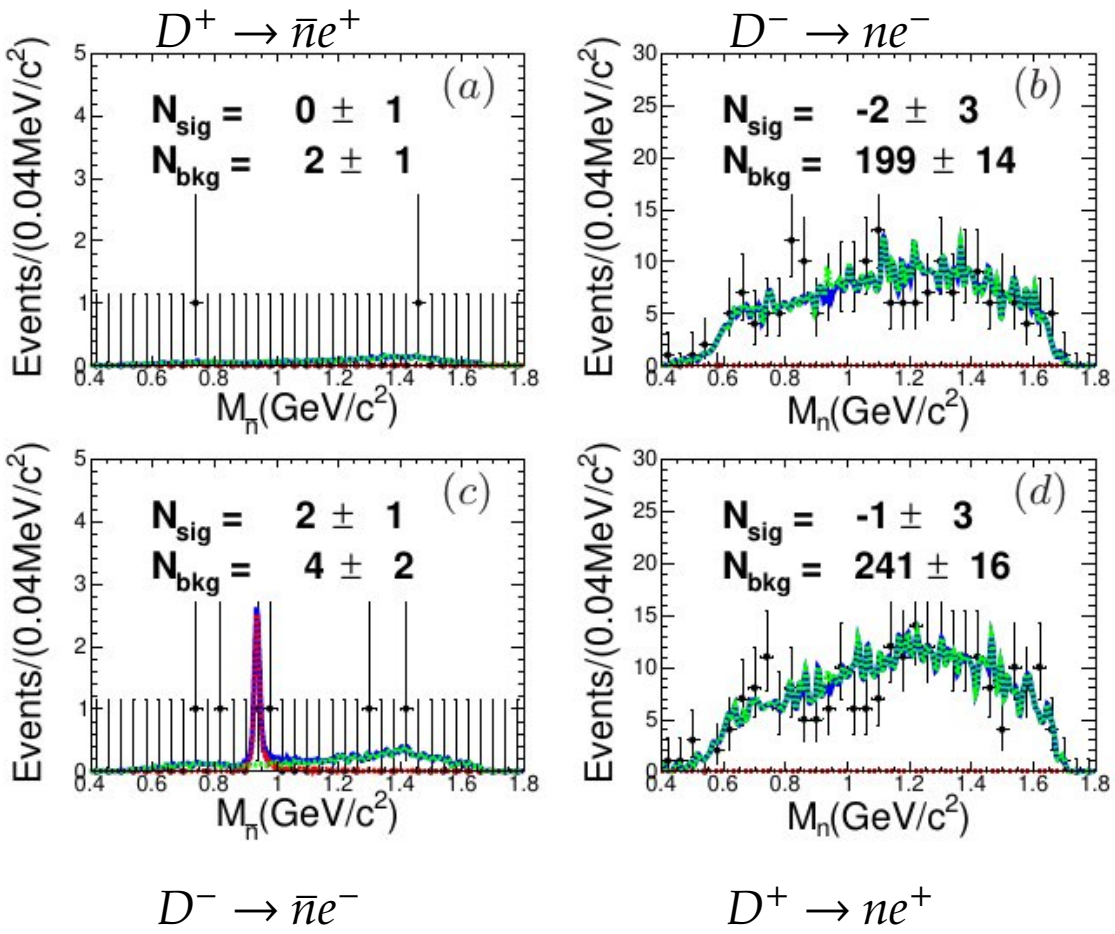
$D^+ \to n(\bar{n})e^+$



Double Tag method

- Using 2.93 fb^{-1} ψ(3770) data
- D^- tagged to suppress non-$D\overline{D}$ backgrounds
- $n(\bar{n})$ regarded as missing particle with momentum & mass inferred from beam condition
- GBDT based on EMC shower shape trained separately for $n(\bar{n})$ to suppress backgrounds such as $D \to \pi^0 X e\nu$ and $D \to K_L^0 X e\nu$
- Fit to $n(\bar{n})$ mass to extract signals

Signal, Background, & Sum



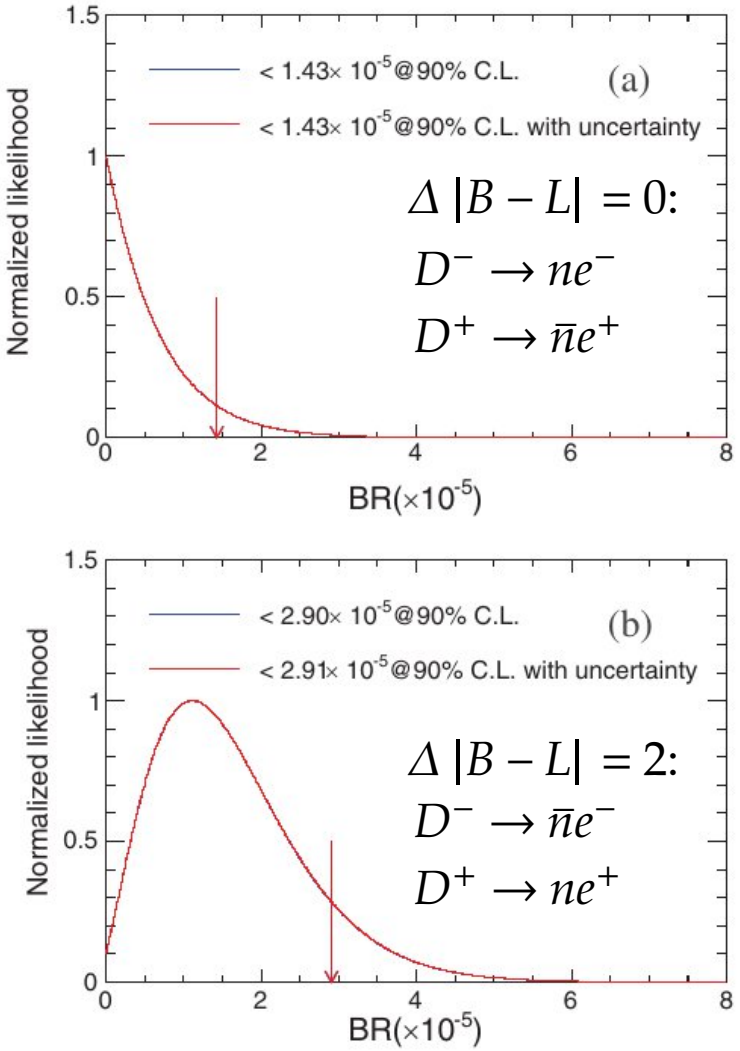
$D^+ \to n(\bar{n})e^+$

- Using 2.93 fb^{-1} ψ(3770) data
- No significant signal found, the UL limits are set:

$$B\left(D^{+(-)} \to \bar{n}\,(n)\,e^{+(-)}\right) < 1.43 \times 10^{-5} \quad \text{w/ } \Delta|B-L| = 0$$

$$B\left(D^{+(-)} \to n\,(\bar{n})\,e^{+(-)}\right) < 2.91 \times 10^{-5} \quad \text{w/ } \Delta|B-L| = 2$$

First searches!



BESIII prospects on FCNC searches

Decay	Upper limit (10^{-6})	Experiment	Year	Ref.	BESIII Expected (10^{-6})
$D^0 \to \pi^0 e^+ e^-$	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	201		1.7

20 fb^{-1} @ 3.773 GeV

6 fb^{-1}@ 4.18 GeV

White Paper
CPC 44 (2020) 040001

Prospects of BELLE II on rare charm decays can be found in *the BELLE II Physics Book*

LHCb prospects

Mode	Upgrade ($50\,\mathrm{fb}^{-1}$)	Upgrade II ($300\,\mathrm{fb}^{-1}$)
$D^0 \to \mu^+\mu^-$	4.2×10^{-10}	1.3×10^{-10}
$D^+ \to \pi^+\mu^+\mu^-$	10^{-8}	3×10^{-9}
$D_s^+ \to K^+\mu^+\mu^-$	10^{-8}	3×10^{-9}
$\Lambda \to p\mu\mu$	1.1×10^{-8}	4.4×10^{-9}
$D^0 \to e\mu$	10^{-9}	4.1×10^{-10}

BF

Mode	Upgrade ($50\,\mathrm{fb}^{-1}$)	Upgrade II ($300\,\mathrm{fb}^{-1}$)
$D^+ \to \pi^+\mu^+\mu^-$	0.2%	0.08%
$D^0 \to \pi^+\pi^-\mu^+\mu^-$	1%	0.4%
$D^0 \to K^-\pi^+\mu^+\mu^-$	0.3%	0.13%
$D^0 \to K^+\pi^-\mu^+\mu^-$	12%	5%
$D^0 \to K^+K^-\mu^+\mu^-$	4%	1.7%

A_{CP}

Summary

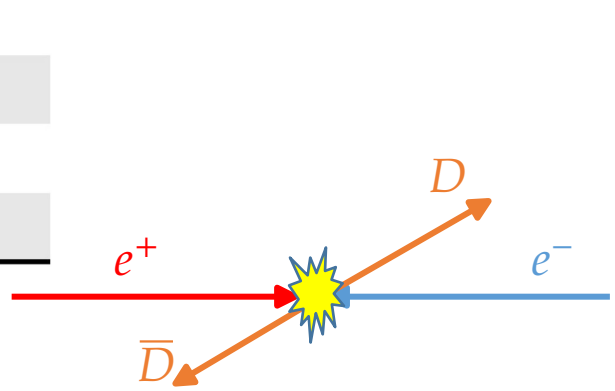
- Charm hadron decays offer unique opportunities for indirect NP searches
- LHCb / BESIII / BELLE(II) are major players in the field:
  - LHCb: Dominant role for charm decays to all-track final states due to overwhelming statistics
  - BESIII/BELLE(II): Advantages in reconstruction of neutrals ($\gamma/\pi^0/\eta/K_S^0/\Lambda$/...) and invisible particles ($\nu/K_L^0/n$/DM/...)
- More results on the way: more decay modes currently under study & more data in coming years from existing experiments
  - Stay tuned!
- STCF is on the horizon! (See CDR link & the talk by Xiaocong on Thursday)

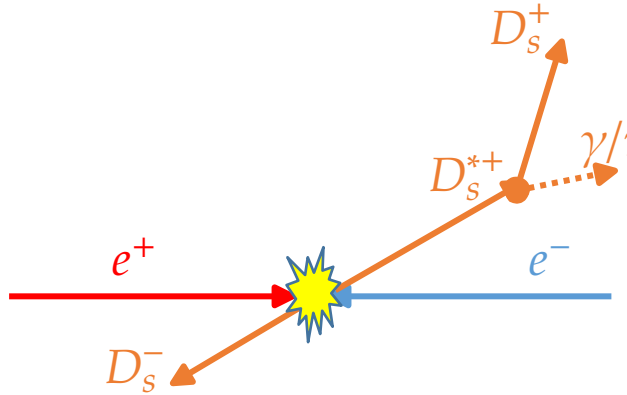
Backup Slides

Charm datasets @ BESIII

- Pairs of $D_{(s)}$ produced near threshold w/o additional hadrons

Data samples	$\sqrt{s}$ (GeV)	Int. $\mathcal{L}$ (fb^{-1})
$D\overline{D}$	3.773	2.93
$D_s\overline{D}_s^*$	4.178	3.19
$D_s\overline{D}_s^*$	4.189 – 4.226	3.18
$\Lambda_c^+\overline{\Lambda}_c^-$	4.599	0.567
$\Lambda_c^+\overline{\Lambda}_c^-$	4.612 – 4.698	3.8

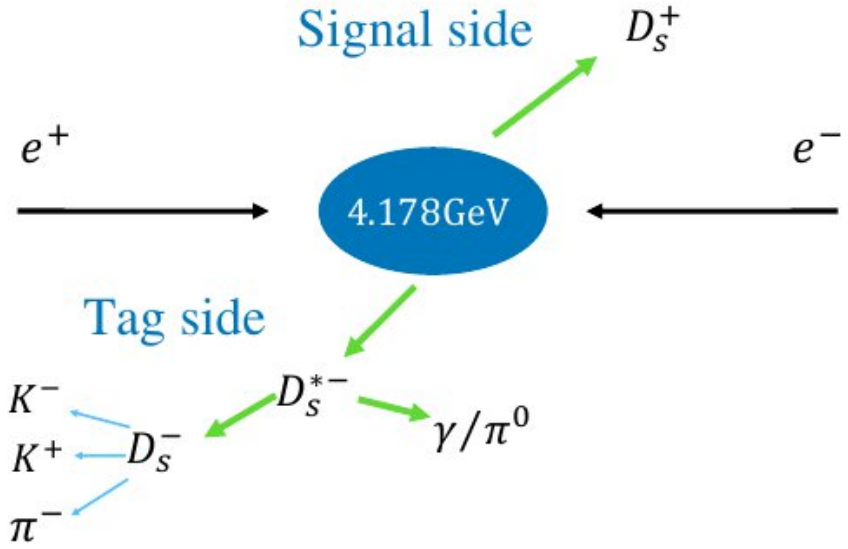




- Advantages:
  - Low background level
  - Full event info, neutrino kinematics can be inferred
  - Absolute branching fraction measurement possible with one $D_{(s)}$ tagged
  - Superb EMC performance on e / γ / π^0

Double-Tag method

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



ST yields:

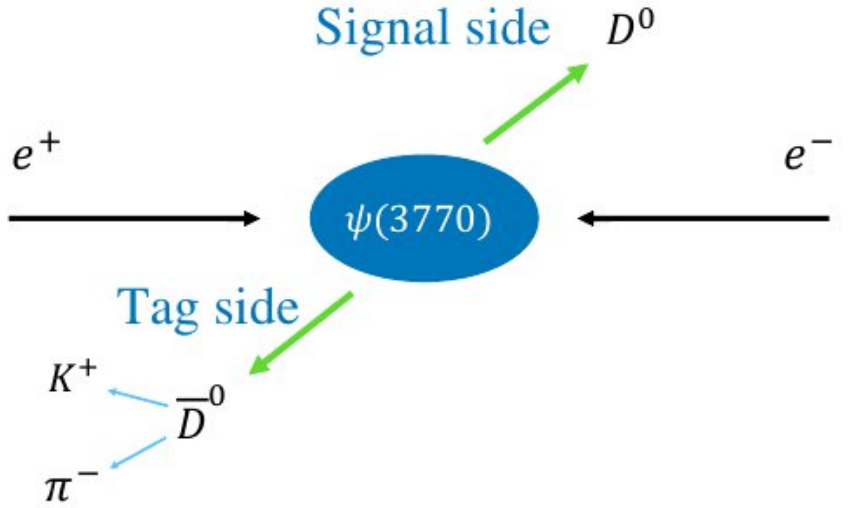
$$N^{ST}_{D_{(s)}} = 2\times N_{D\bar{D}} \times B_{ST} \times \varepsilon_{ST}$$

DT yield:

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

The signal branching fraction:

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



New (inclusive) tagging method currently under study to further improve DT efficiency

BESIII Λ_c^+ samples

$\sqrt{s}$ (MeV)	$\mathcal{L}_{\rm int}$ (pb^{-1})
$4599.53 \pm 0.07 \pm 0.74$	$586.90 \pm 0.10 \pm 3.90$
$4611.84 \pm 0.12 \pm 0.28$	$103.45 \pm 0.05 \pm 0.64$
$4628.00 \pm 0.06 \pm 0.31$	$519.93 \pm 0.11 \pm 3.22$
$4640.67 \pm 0.06 \pm 0.36$	$548.15 \pm 0.12 \pm 3.40$
$4661.22 \pm 0.06 \pm 0.29$	$527.55 \pm 0.12 \pm 3.27$
$4681.84 \pm 0.08 \pm 0.29$	$1664.34 \pm 0.21 \pm 10.32$
$4698.57 \pm 0.10 \pm 0.32$	$534.40 \pm 0.12 \pm 3.31$

TABLE II. The ΔE requirement, ST yield, and ST detection efficiency (include the branching fractions of subleading decays) of $\bar{\Lambda}_c^- \to \bar{\Sigma}^-\gamma$ for each tag mode for the data sample at $\sqrt{s} = 4.600$ GeV. The uncertainty in the ST yield is statistical only.

Tag mode	ΔE (MeV)	$N_i^{\rm ST}$	$\epsilon_i^{\rm ST}$ (%)
$\bar{p}K^+\pi^-$	$(-34, 20)$	6705 ± 90	51.0
$\bar{p}K_S$	$(-20, 20)$	1268 ± 37	56.2
$\bar{\Lambda}\pi^-$	$(-20, 20)$	741 ± 28	47.7
$\bar{p}K^+\pi^-\pi^0$	$(-30, 20)$	1539 ± 57	15.4
$\bar{p}K_S\pi^0$	$(-30, 20)$	485 ± 29	18.4
$\bar{\Lambda}\pi^-\pi^0$	$(-30, 20)$	1382 ± 49	16.6
$\bar{p}K_S\pi^+\pi^-$	$(-20, 20)$	512 ± 29	19.9
$\bar{\Lambda}\pi^-\pi^+\pi^-$	$(-20, 20)$	646 ± 31	13.7
$\bar{\Sigma}^0\pi^-$	$(-20, 20)$	404 ± 22	22.5
$\bar{\Sigma}^-\pi^+\pi^-$	$(-30, 20)$	872 ± 38	18.1