Search for Radiative/Rare/Forbidden Decays of Charm Hadrons

Liang Sun
Wuhan U.

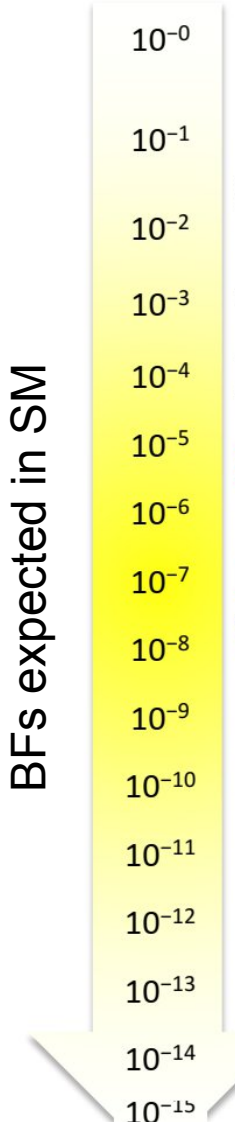
2025/06/30

第三届BESIII-Belle II-LHCb粲强子物理联合研讨会

Outline

- Background info
- A selection of recent results on
  - Weak radiative charm hadron decays
  - FCNC related decays ($h\nu\bar{\nu}$, $hh'e^+e^-$)
  - LNV decays
  - BNV decays
  - Search for massless dark photon in $c \to u\gamma'$
- 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

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)

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

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

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

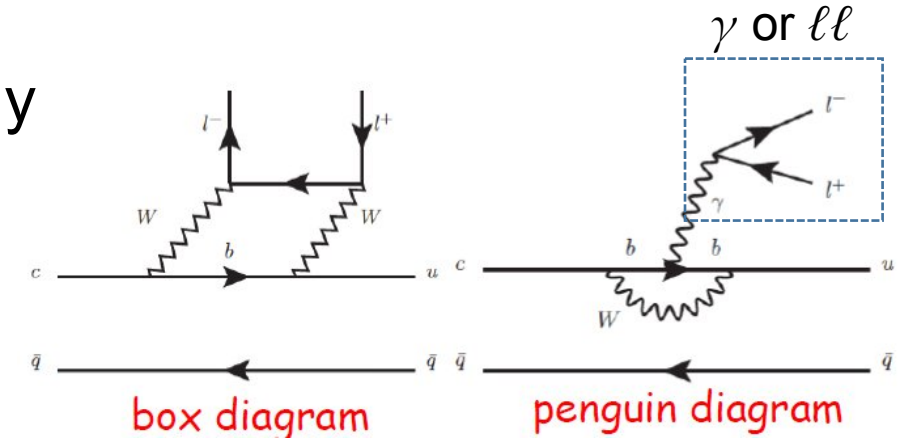
$D \to (h)\mu^+e^-$

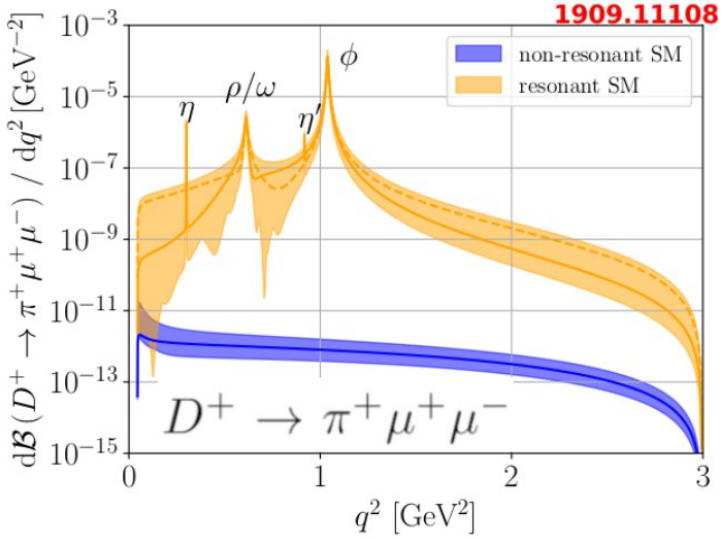
$D \to (h)pe^-$

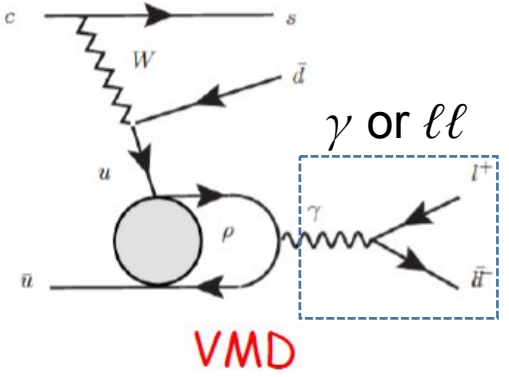
(NP)
Forbidden decays: LNV, LFV, BNV

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 $D \to \gamma X$
- VMD insignificant in $D \to X\nu\bar{\nu}$





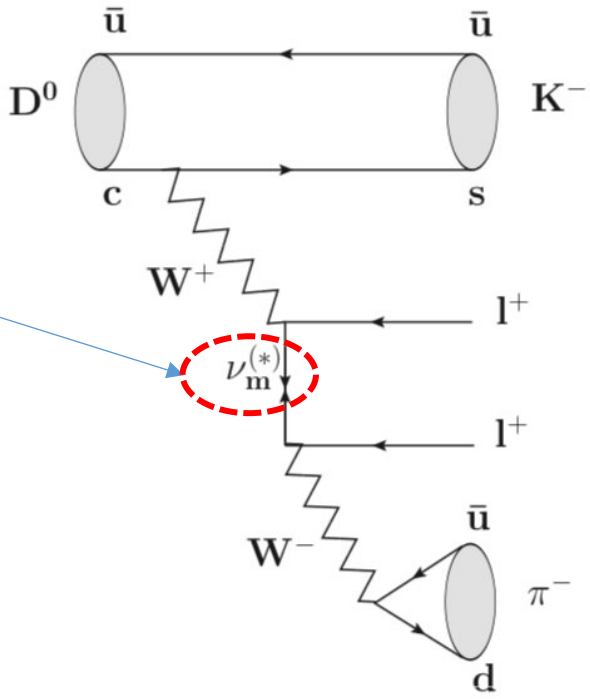


Lepton Number Violation

- **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

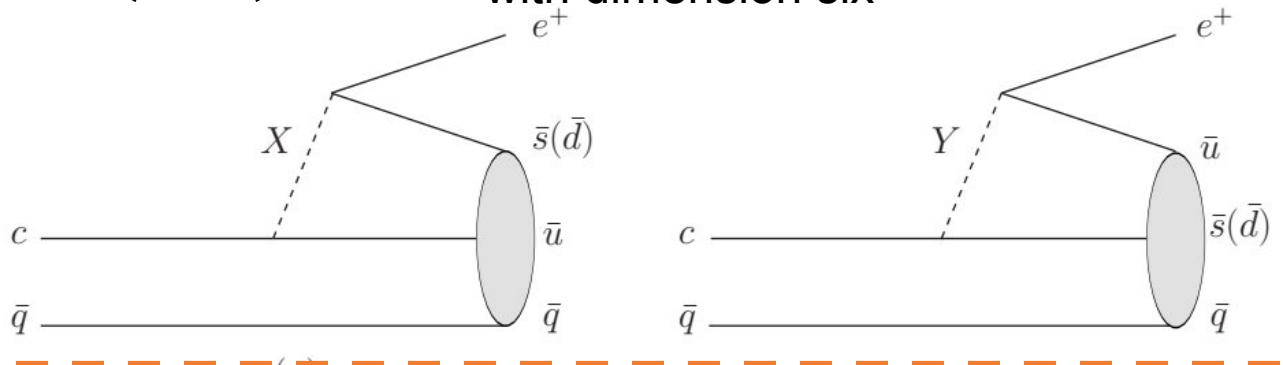


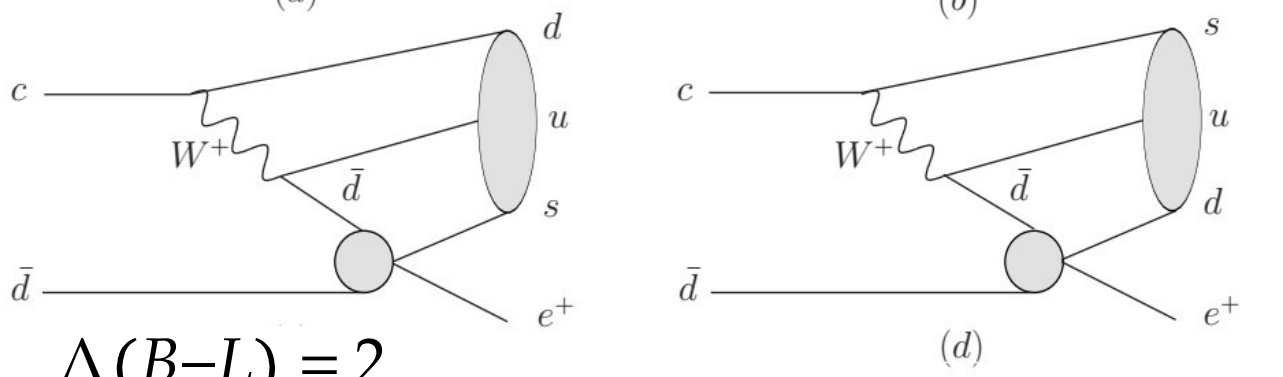
Baryon **N**umber **V**iolation

- 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

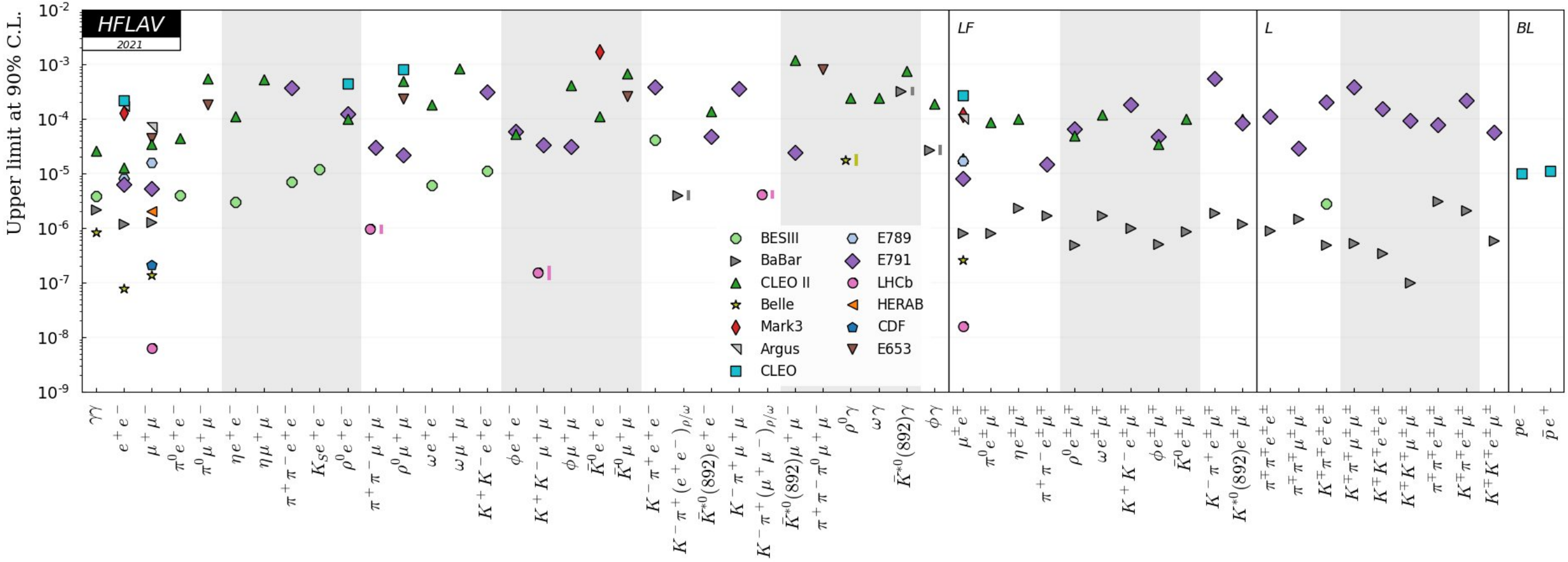




$\Delta(B-L) = 2$

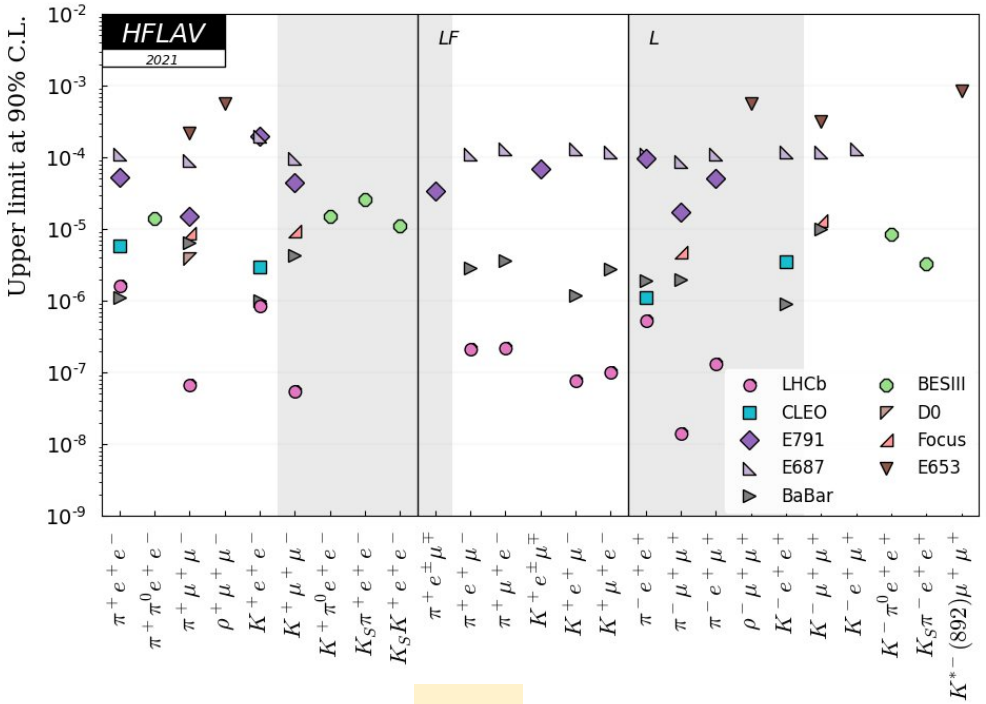
Feynman diagrams under operators with dimension seven

Results on rare charm decays (D^0)

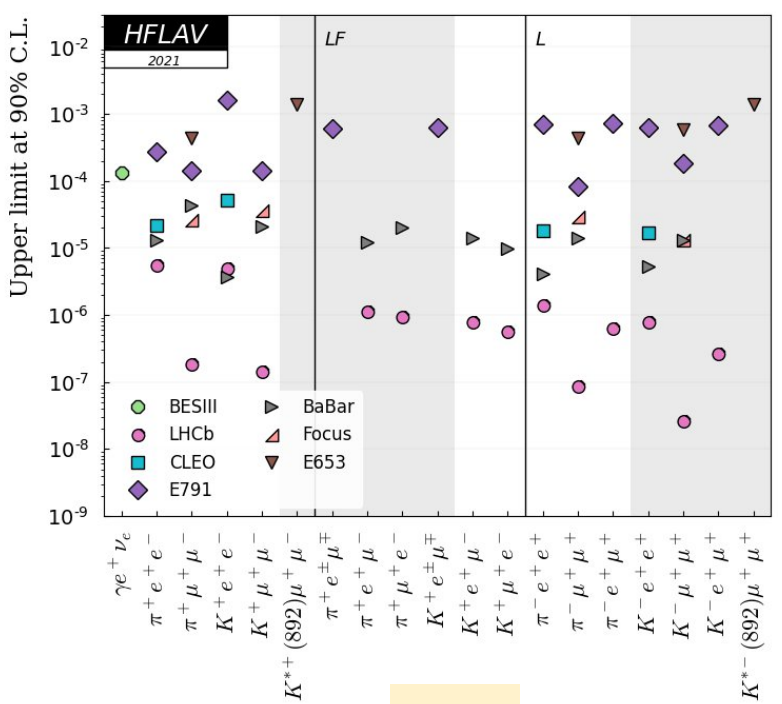


https://hflav-eos.web.cern.ch/hflav-eos/charm/rare/Spring2021/rare_charm.html

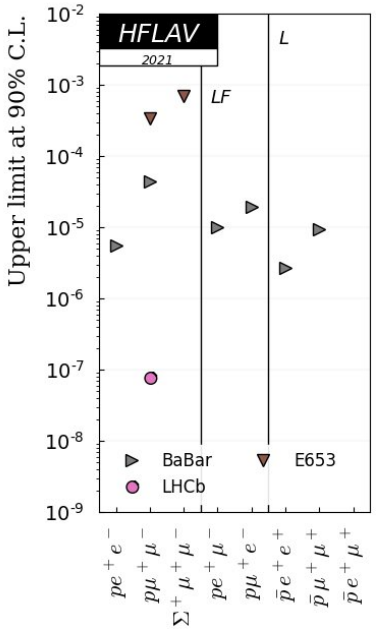
Results on rare charm decays



D^+



D_s^+



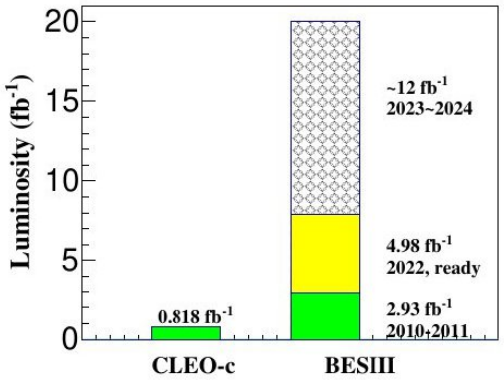
Λ_c^+

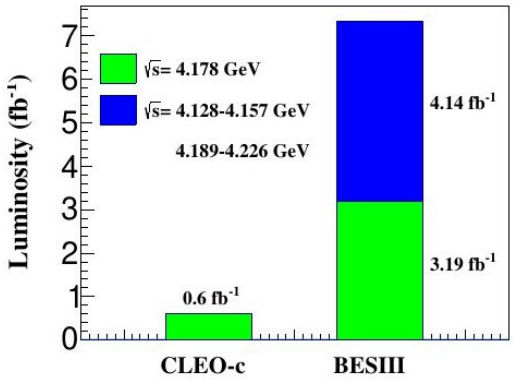
Still lots of unexplored channels…

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

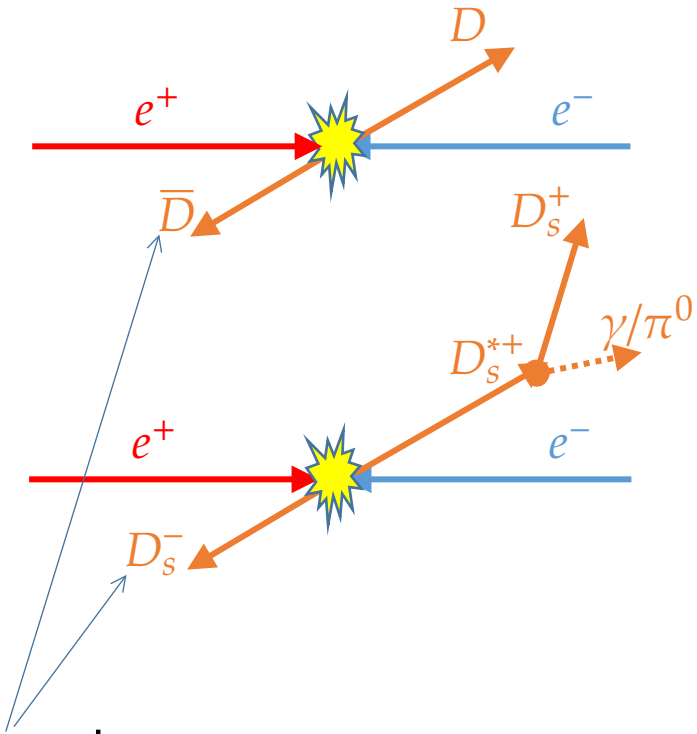
Charm datasets @ BESIII

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





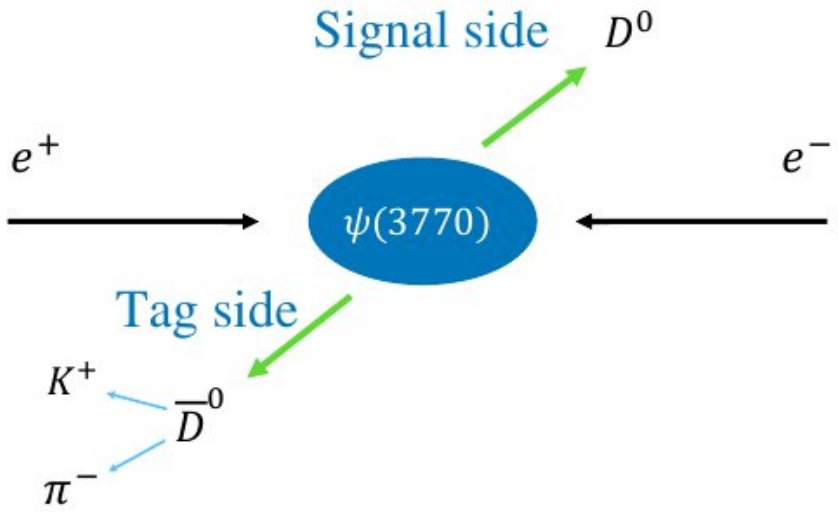
- $e^+e^- \to \psi(3770) \to D\bar{D}$, $\mathcal{L}_{\rm int}$ =2.93+4.98 (+12) fb^{-1}
- $e^+e^- \to D_sD_s^*$, $\sqrt{s} = 4.128 - 4.226$ GeV, $\mathcal{L}_{\rm int}$=7.33 fb^{-1}



- 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:

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

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:

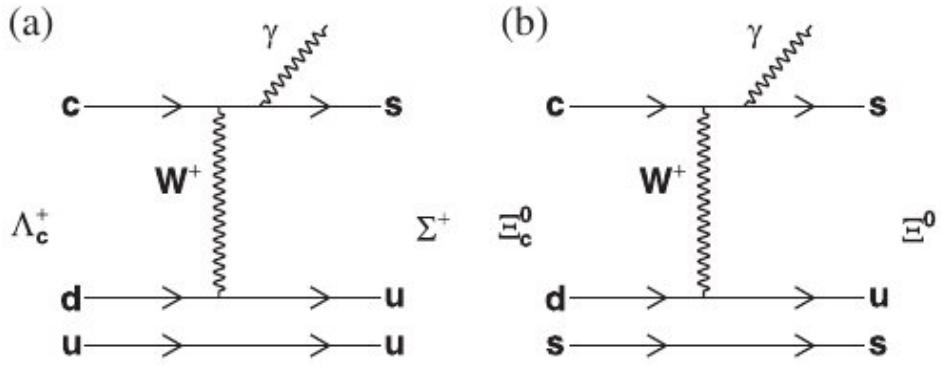
$$B_{sig} = \frac{N^{signal}_{DT}}{N^{ST}_{D_{(s)}} \times \varepsilon}$$

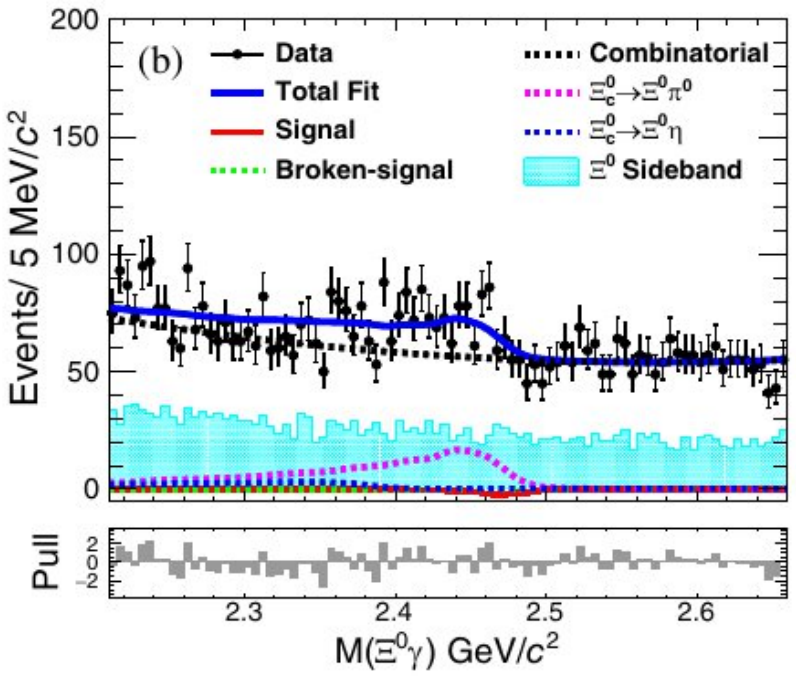
PRD 107 (2023) 032001

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

- First search for weak radiative decays of charm baryons
- Using 980 fb^{-1} Belle data
- Normalized to decays of $\Lambda_c^+ \to pK^-\pi^+$ and $\Xi_c^0 \to \Xi^+\pi^+$
- Data-driven method to determine peaking contributions from $\Xi_c^0 \to \Xi^0\pi^0$ and $\Xi_c^0 \to \Xi^0\eta$
- No obvious signal found, upper limit determined @ 90% CL:

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

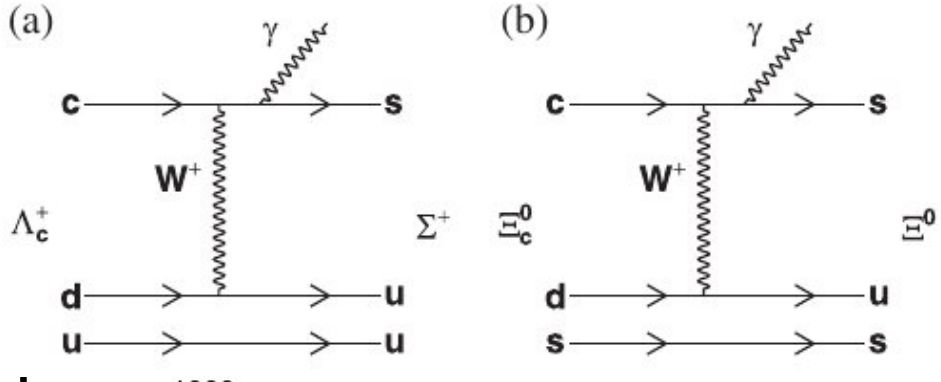


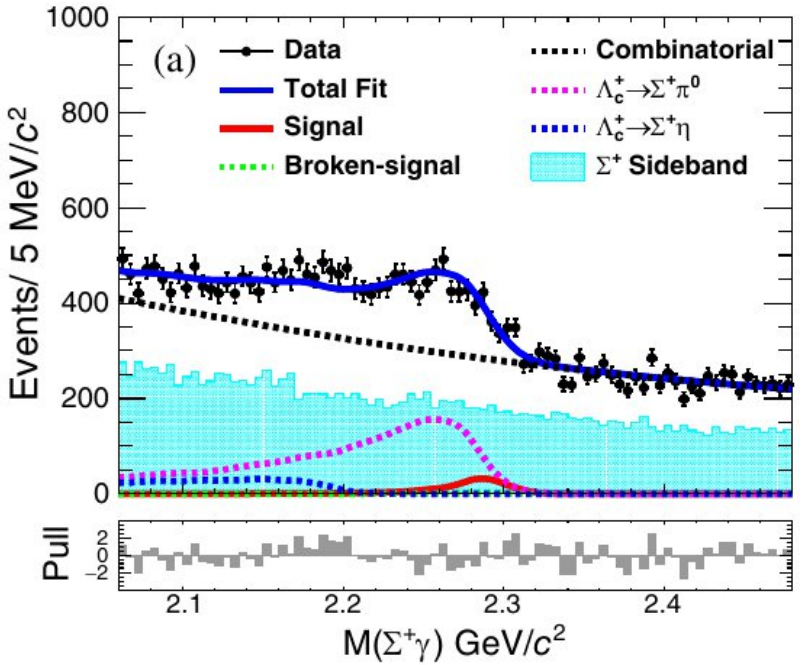


Search for $\Lambda_c^+ \to \Sigma^+\gamma$ and $\Xi_c^0 \to \Xi^0\gamma$

- First search for weak radiative decays of charm baryons
- Using 980 fb^{-1} Belle data
- Normalized to decays of $\Lambda_c^+ \to pK^-\pi^+$ and $\Xi_c^0 \to \Xi^+\pi^+$
- Data-driven method to determine peaking contributions from $\Xi_c^0 \to \Xi^0\pi^0$ and $\Xi_c^0 \to \Xi^0\eta$
- No obvious signal found, upper limit determined @ 90% CL:

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

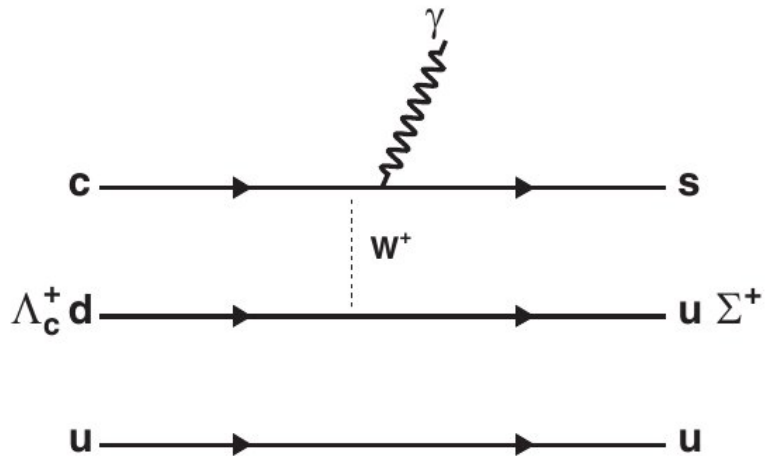


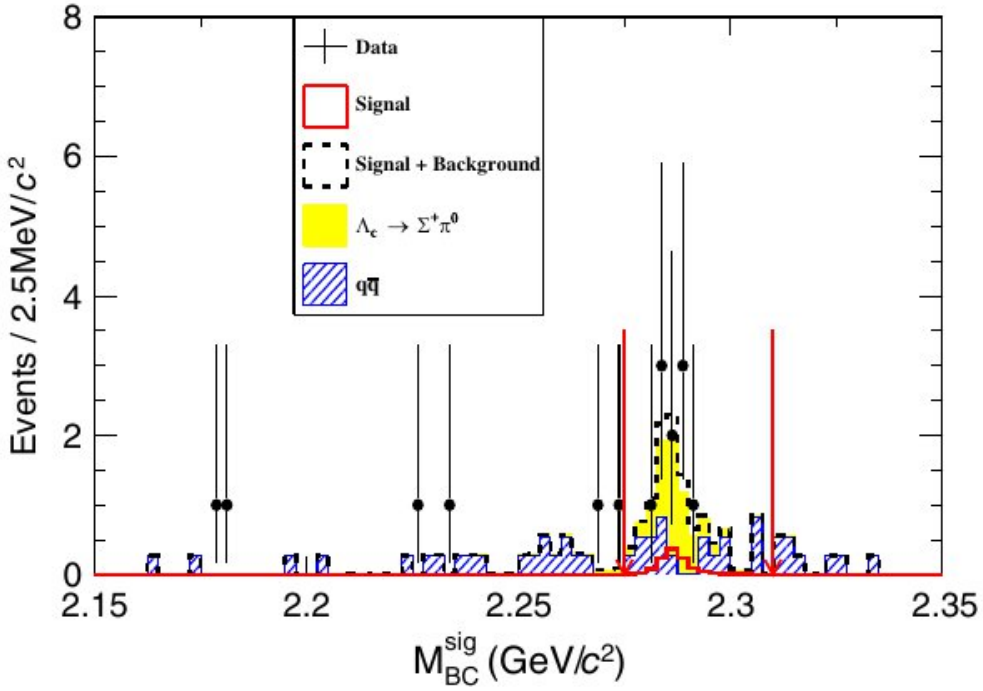


Search for $\Lambda_c^+ \to \Sigma^+ \gamma$

- Using 4.5 fb^{-1} data @ $E_{cm} \in [4.6, 4.7]$ GeV
- Double-tag method with $\overline{\Lambda}_c^-$ reconstructed in 10 hadronic decay modes
- Peaking background of $\Lambda_c^+ \to \Sigma^+ \pi^0$ determined from MC
- Upper limit @ 90% CL is set:

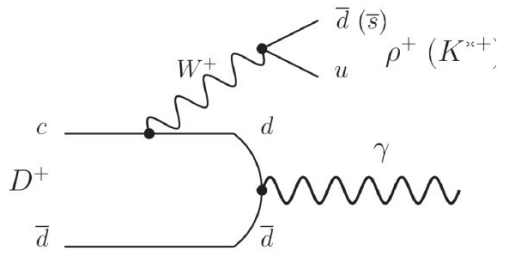
$$\mathcal{B}(\Lambda_c^+ \to \Sigma^+ \gamma) < 4.4 \times 10^{-4}$$

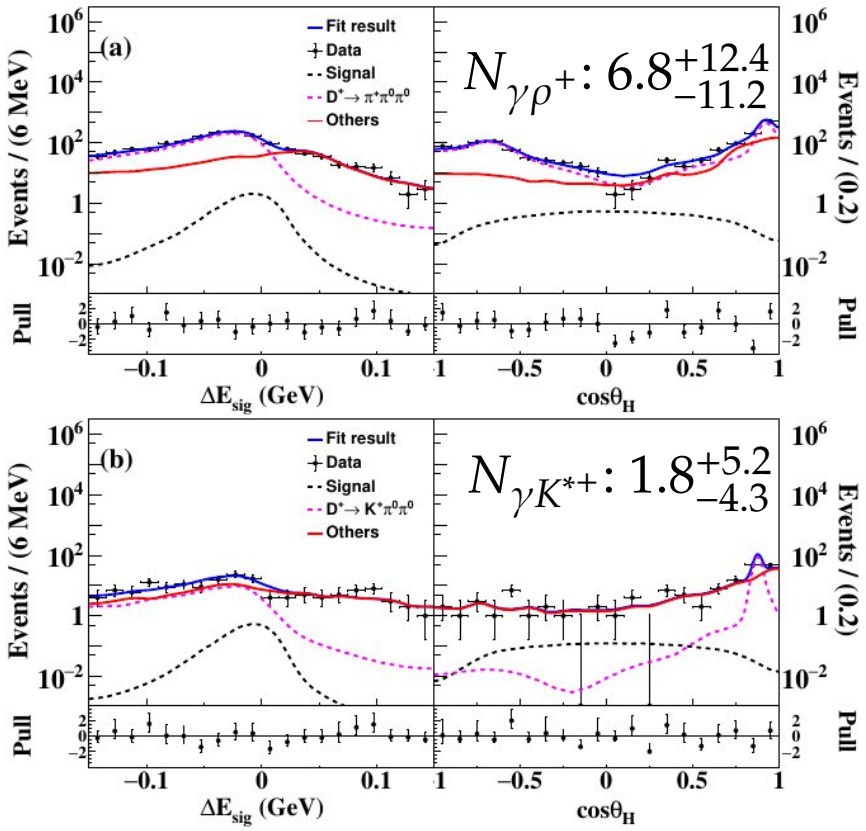




Search for $D^+ \to \gamma\rho^+$ and $D^+ \to \gamma K^{*+}$

- First search for radiative D^+ decays
- Using 20.3 fb^{-1} data @ E_{cm} = 3.773 GeV
- Double-tag method with D^- reconstructed in 6 hadronic decay modes
- Requiring $\rho^+(K^{*+}) \to \pi^+(K^+)\pi^0$
- Upper limits @ 90% CL are set:
  - $B(D^+ \to \gamma\rho^+) < 1.3 \times 10^{-5}$
  - $B(D^+ \to \gamma K^{*+}) < 1.8 \times 10^{-5}$

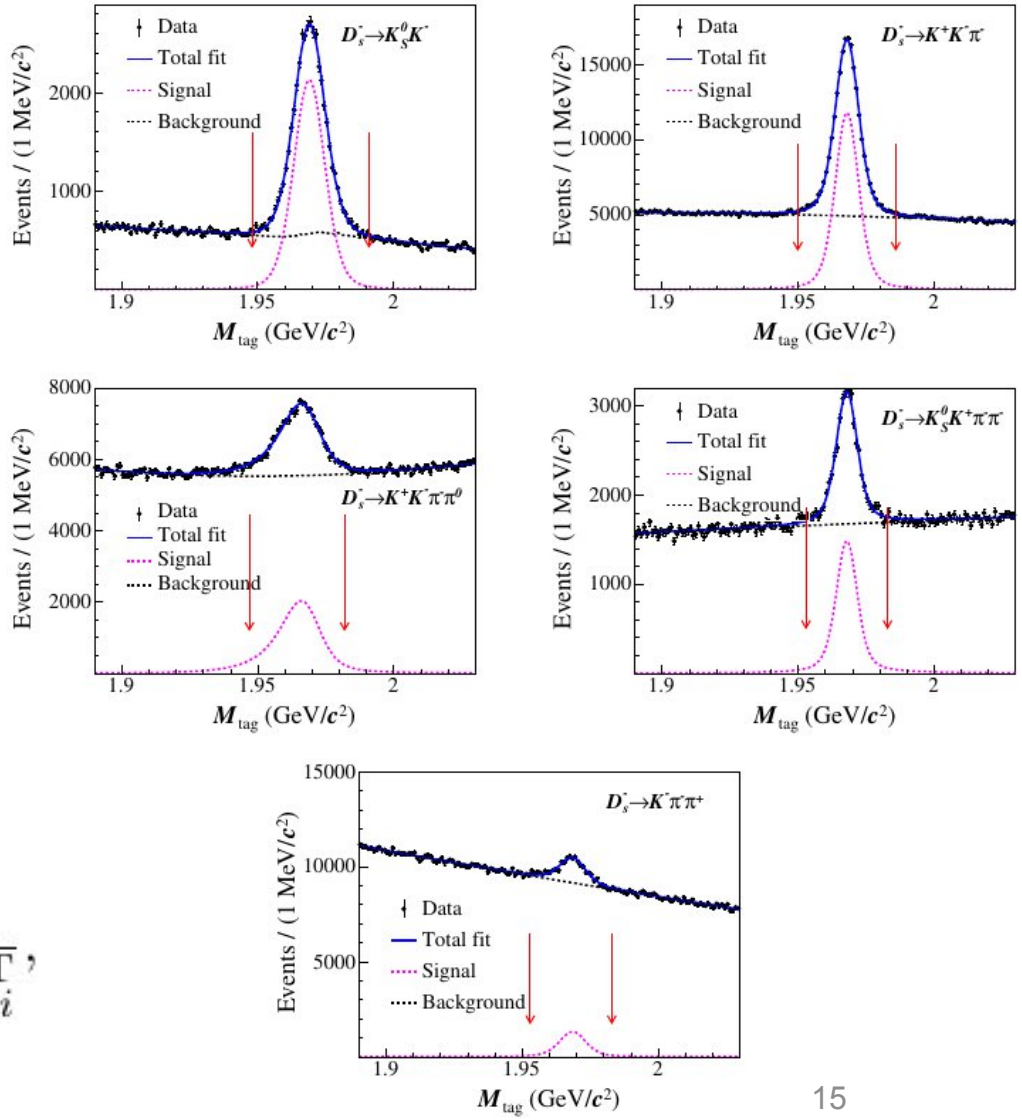




Search for $D_s^+ \to \gamma\rho(770)^+$

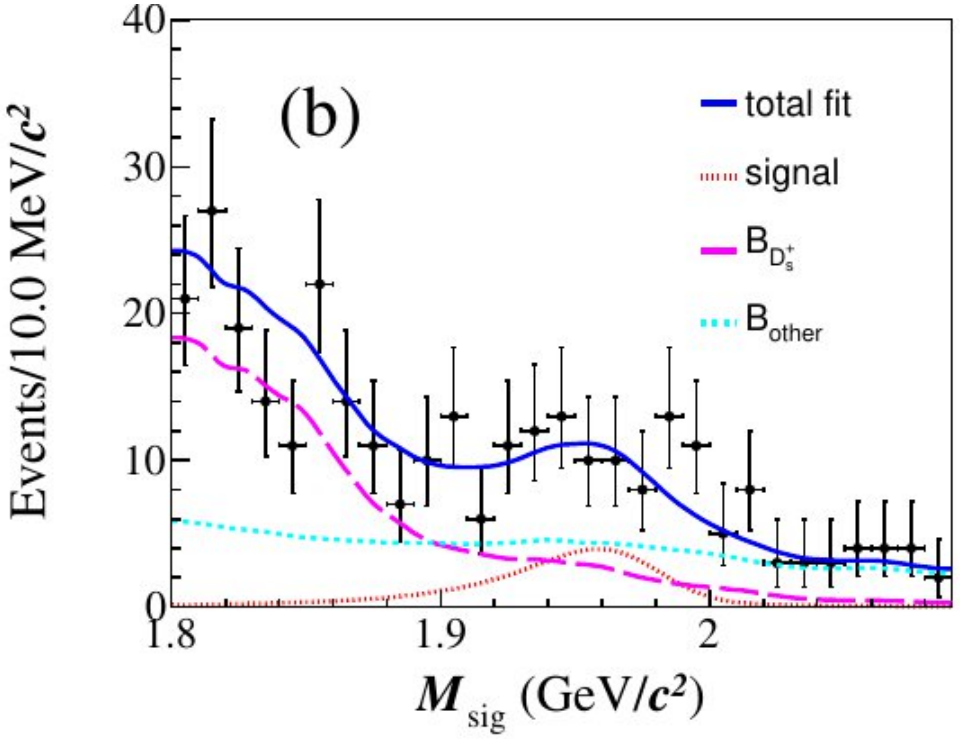
- First search for a radiative D_s^+ decay
- BF important to test QCD-based LD calculations & predictions of CPV in D decays
- 7.33 fb^{-1} data @ $E_{cm} \in [4.128, 4.226]$ GeV
- Double-tag method with five modes

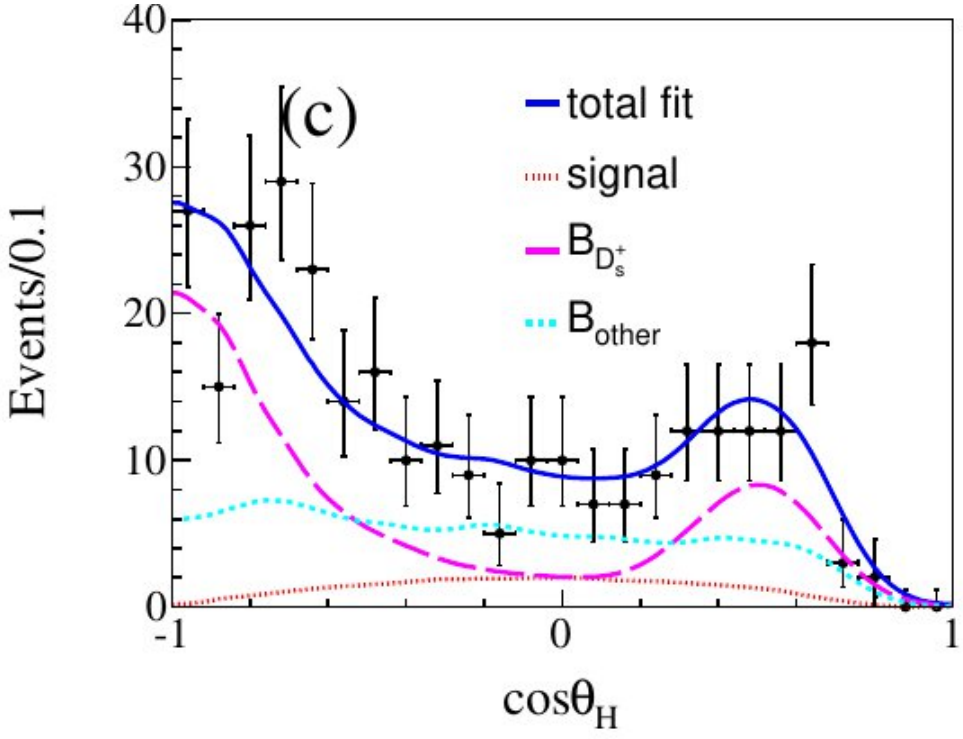
$$\mathcal{B}(D_s^+ \to \gamma\rho(770)^+) = \frac{N_{\rm total}^{\rm DT}}{B(\pi^0 \to \gamma\gamma)\sum_{\alpha,i} N_{\alpha,i}^{\rm ST}\epsilon_{\alpha,i}^{\rm DT}/\epsilon_{\alpha,i}^{\rm ST}},$$



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

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



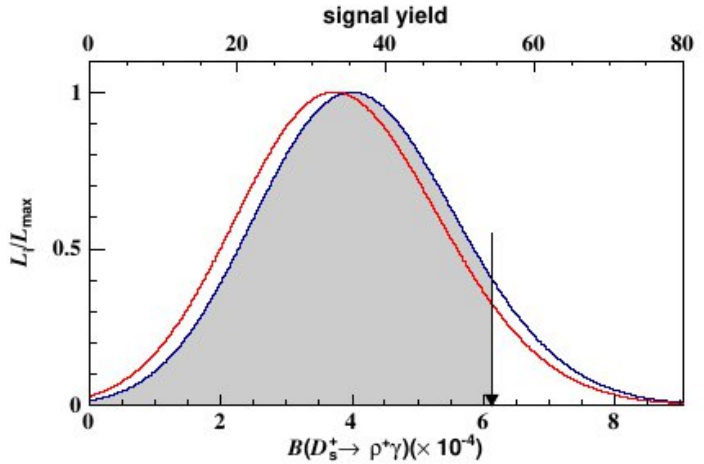


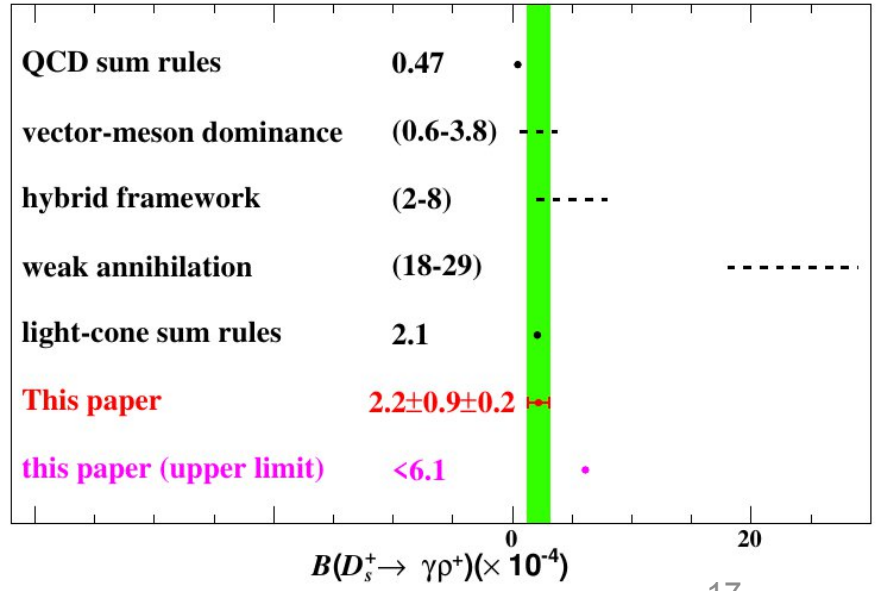
Search for $D_s^+ \to \gamma\rho(770)^+$

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

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

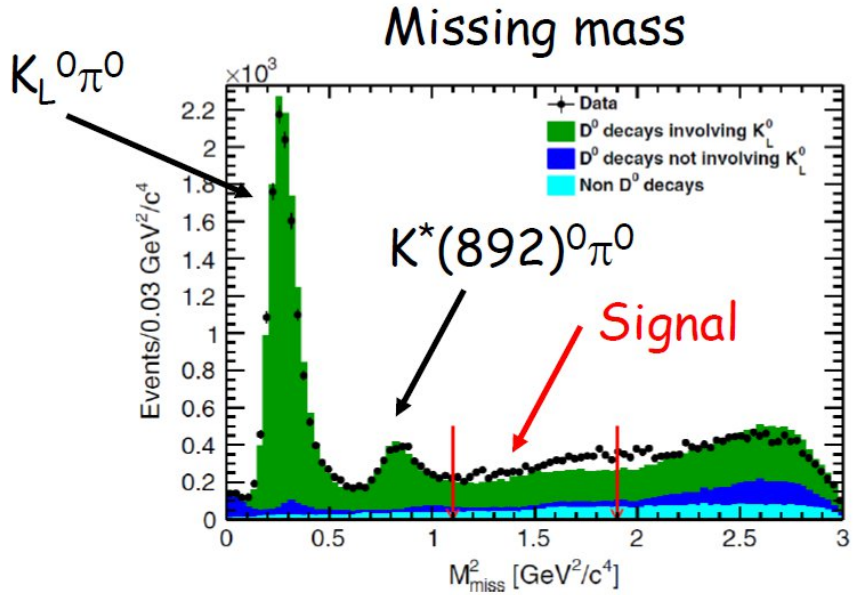
with UL set at $< 6.1 \times 10^{-4}$ @ 90% CL

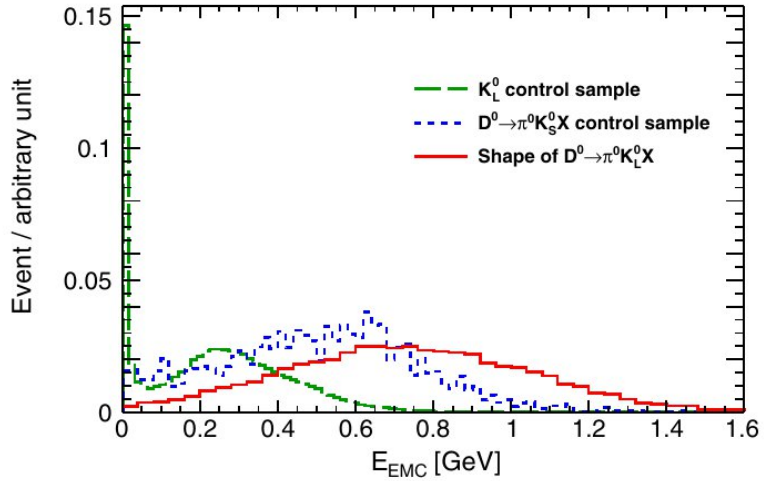




Search for $D^0 \to \pi^0 \nu\bar{\nu}$

- 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 ($E_{\rm EMC}^{K_L^0}$) 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 ($E_{\rm EMC}^{X}$) and K_L^0 kinematics using data sample of $D^0 \to \pi^0 K_S^0 (\pi^+\pi^-) X$
  - $E_{\rm EMC} = E_{\rm EMC}^{K_L^0} + E_{\rm EMC}^{X}$





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

PRD 105 (2022) L071102

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

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

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

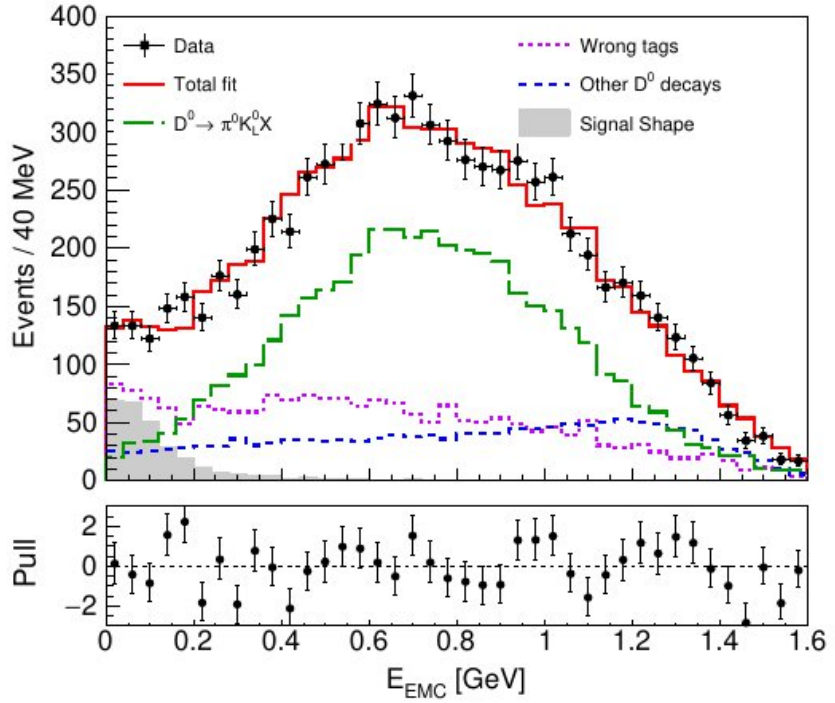
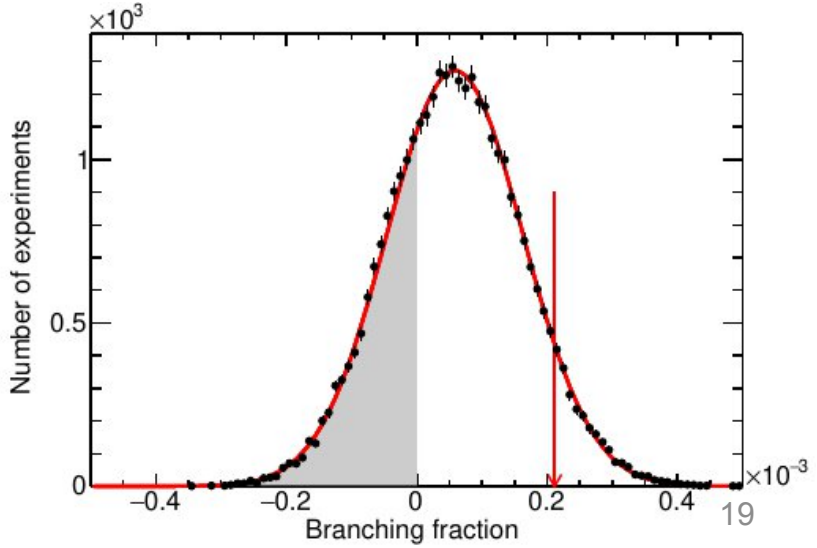


TABLE I. Summary of systematic uncertainties on the signal yield and detection efficiencies.

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



PRL 133 (2024) 121801
JHEP 01 (2025) 109

Search for $D_s^+ \to hh'ee$ decays

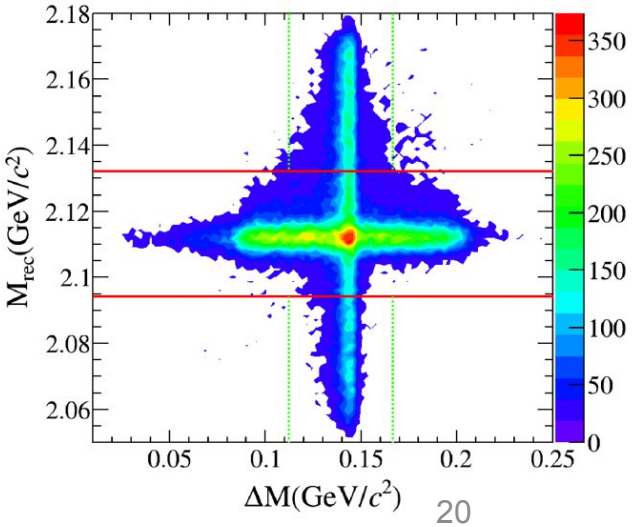
- First search for four-body D_s^+ decays to an electron pair
- Using 7.33 fb^{-1} data @ 4.128-4.226 GeV
- D_s^+ mainly from $e^+e^- \to D_s^{*\pm}D_s^{\mp}$, with total number of $N_{D_s^{\pm}D_s^{\mp}} = (64.7 \pm 0.3) \pm 10^5$
- Single-tag method, the BF for a given channel is given by:

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

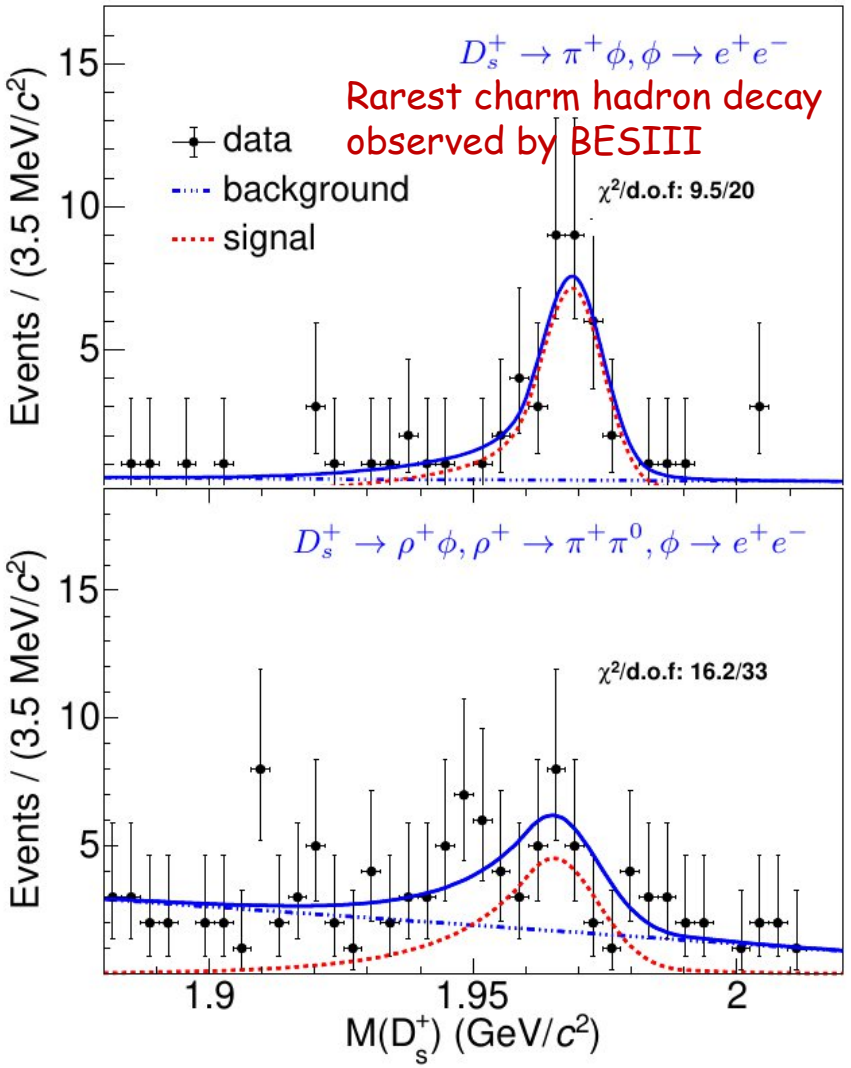
- 2D optimization of requirements on M_{rec} vs. ΔM

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

PRD 104, 012016 (2021)



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



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

Decay	N_{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

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

[JHEP 05 (2024) 293]

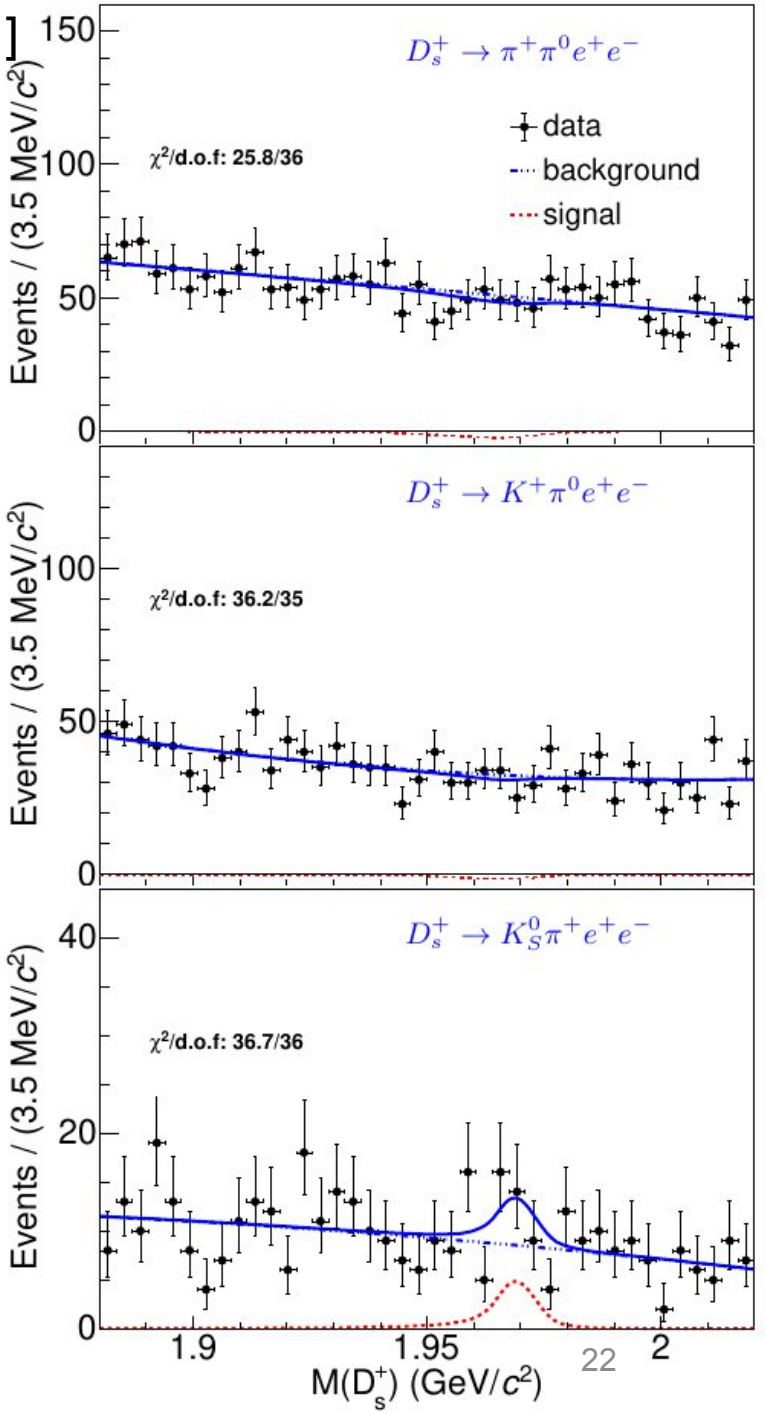
[PRL 133 (2024) 121801]

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

- FCNC $c \to u e^+ e^-$ process, highly suppressed in SM
- Exclusion of events with $M(e^+e^-) \in [0.96, 1.05]$ GeV for mode $\pi^+\pi^0 e^+ e^-$
-

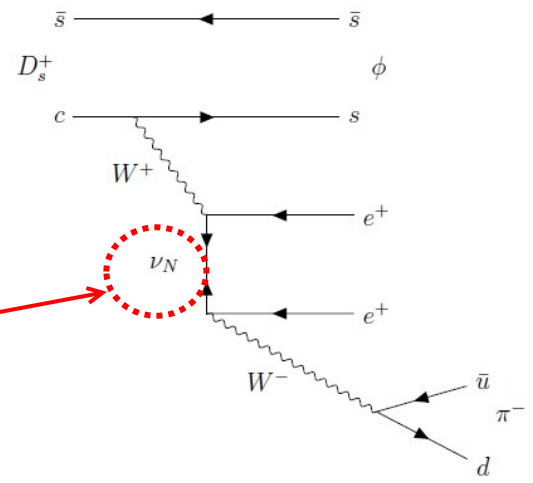
Decay	$N_{\rm sig}$	ϵ (%)	$\mathcal{B}$ ($\times 10^{-5}$)
$D_s^+ \to \pi^+\pi^0 e^+ e^-$	...	7.4	< 7.0
$D_s^+ \to K^+\pi^0 e^+ e^-$	...	5.3	< 7.1
$D_s^+ \to K_S^0\pi^+ e^+ e^-$	...	6.7	< 8.1

All first upper limits!



JHEP 01 (2025) 109

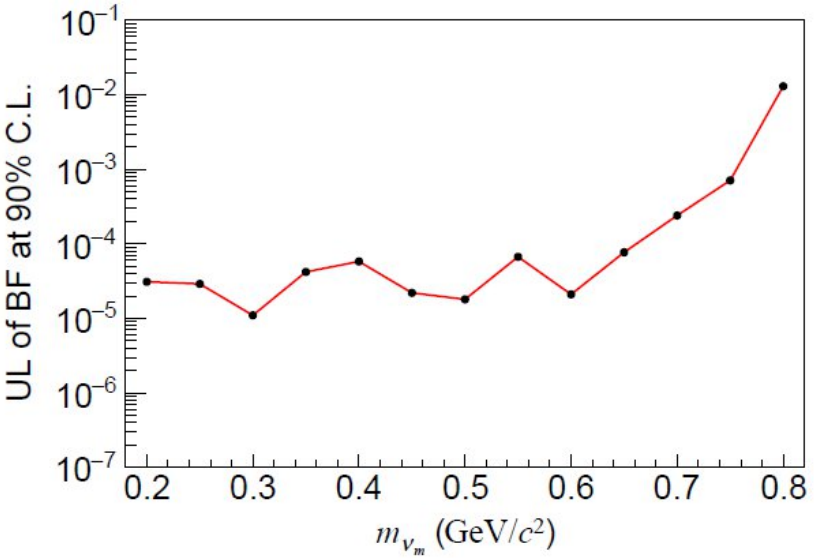
Search for $D_s^+ \to h^- h^0 e^+ e^+$



- LNV ($\Delta L = 2$) process could be mediated by a single Majorana neutrino
- First upper limits @ 90% CL:

Decay channel	ϵ (%)	$\mathcal{B}_{\rm UL}$ ($\mathcal{B}_{\rm UL}^{\rm expected}$)
$D_s^+ \to \phi\pi^- e^+ e^+$	3.0 ± 0.1	$6.9\ (3.5) \times 10^{-5}$
$D_s^+ \to \phi K^- e^+ e^+$	1.8 ± 0.1	$9.9\ (10.8) \times 10^{-5}$
$D_s^+ \to K_S^0 \pi^- e^+ e^+$	6.4 ± 0.1	$1.3\ (2.4) \times 10^{-5}$
$D_s^+ \to K_S^0 K^- e^+ e^+$	4.0 ± 0.1	$2.9\ (2.3) \times 10^{-5}$
$D_s^+ \to \pi^- \pi^0 e^+ e^+$	6.4 ± 0.1	$2.9\ (2.7) \times 10^{-5}$
$D_s^+ \to K^- \pi^0 e^+ e^+$	5.1 ± 0.1	$3.4\ (3.9) \times 10^{-5}$

$D_s^+ \to \phi\pi^- e^+ e^+$ (CF)



First mass scan in a $D \to V\ell\nu_m$ process

PRD 105 (2022) 032006

Search for $D^0 \to pe$

- Flavor of D determined from tag side
- Background suppression with:

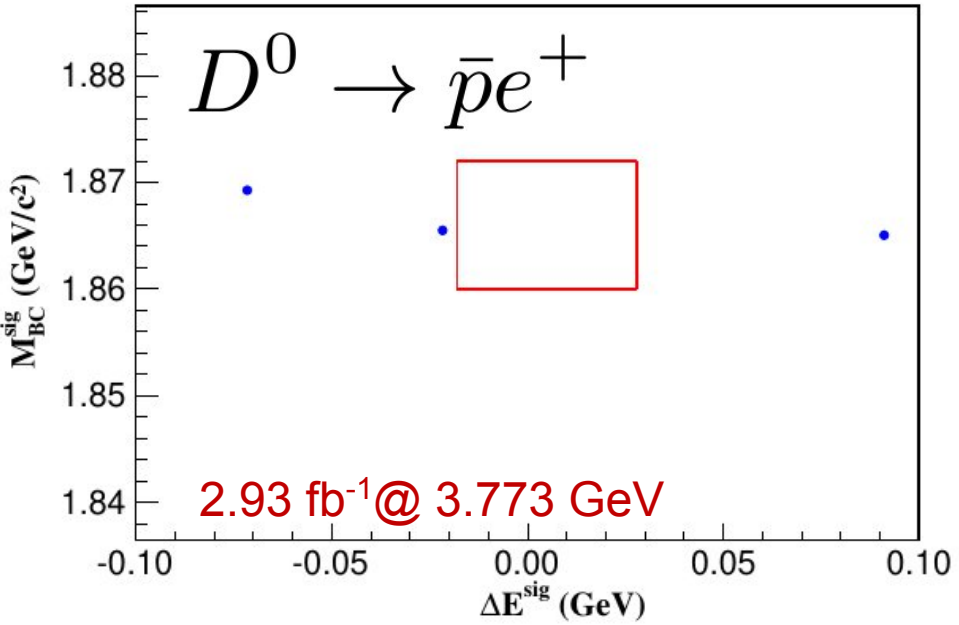
Energy difference: $\Delta E = E_{D0bar} - E_{beam}$

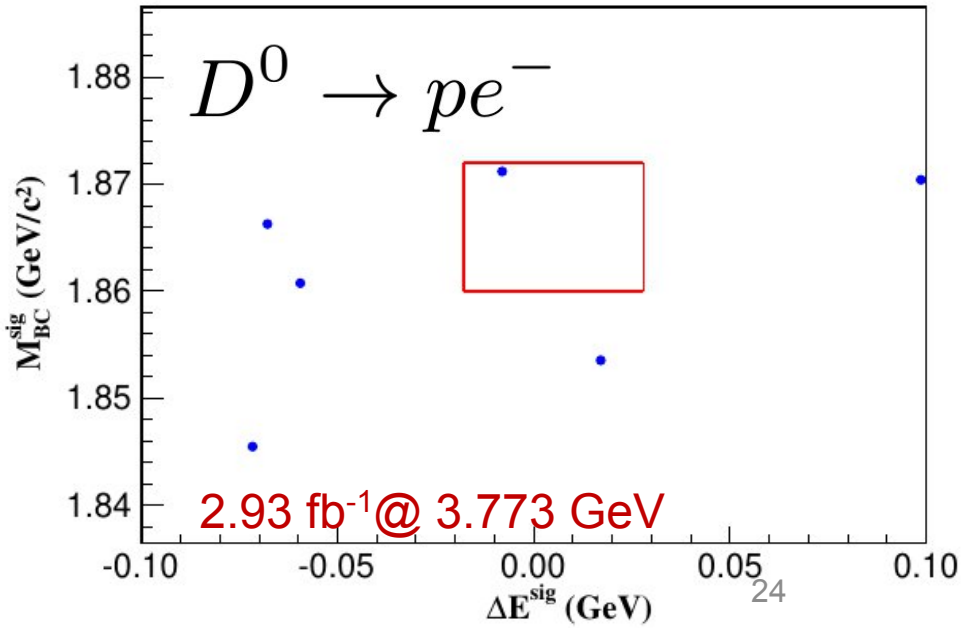
Beam constrained mass: $M_{BC} = \sqrt{E_{beam}^2/c^4 - |\vec{p}_{\bar{D}^0}|^2/c^2}$

- Almost background free
- No signal found, upper limits @ 90% CL are set:

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

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





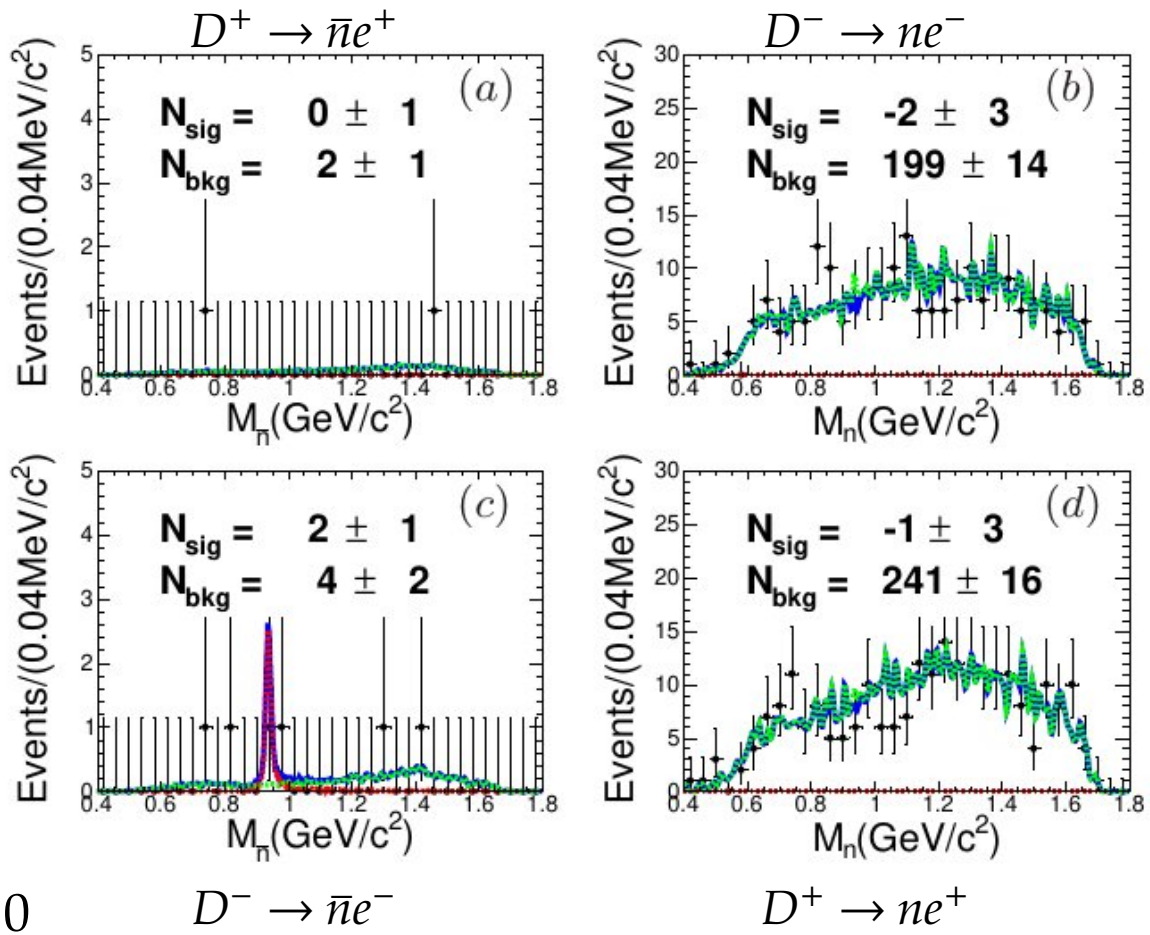
Search for $D^+ \to n(\bar{n})e^+$

- D^- tagged to suppress non-D$\overline{\text{D}}$ backgrounds
- $n(\bar{n})$ regarded as missing particle
- GBDT based on EMC shower shape trained to suppress background
- Fit to $n(\bar{n})$ mass to extract signals
- Upper limits @ 90% CL are set:

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

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

2.93 fb^{-1}@ 3.773 GeV

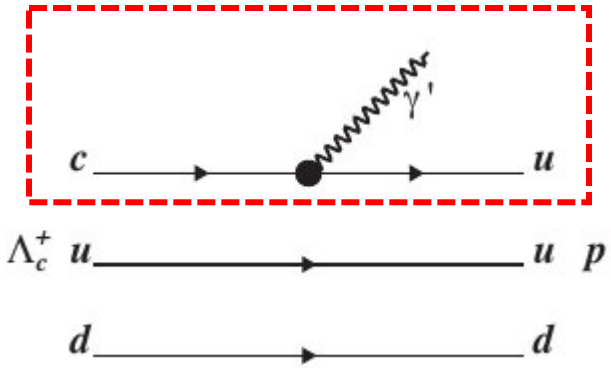


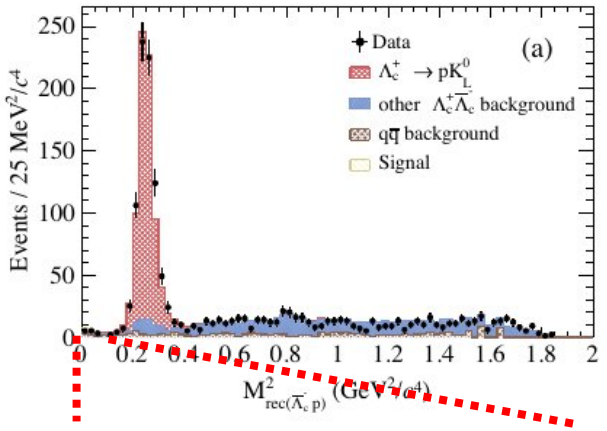
PRD 106 (2022) 072008

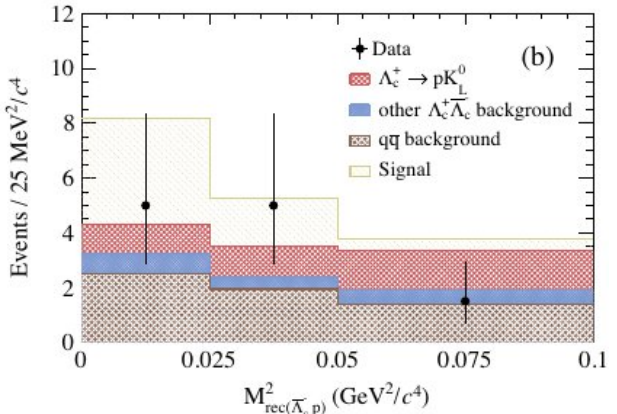
Search for a massless dark photon in $\Lambda_c^+ \to p\gamma'$

- Using 4.5 fb^{-1} data @ $E_{cm} \in [4.6, 4.7]$ GeV
- Double-tag method with $\overline{\Lambda}_c^-$ reconstructed in 10 hadronic decay modes
- Peaking background of $\Lambda_c^+ \to pK_L$ determined from MC
- Upper limit @ 90% CL is set for the first time:

$$\mathcal{B}(\Lambda_c^+ \to p\gamma') < 8.0 \times 10^{-5}$$

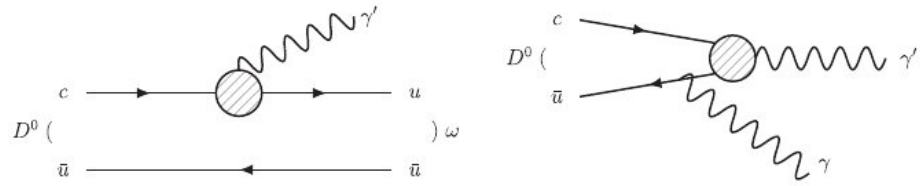






PRD 106 (2022) 072008

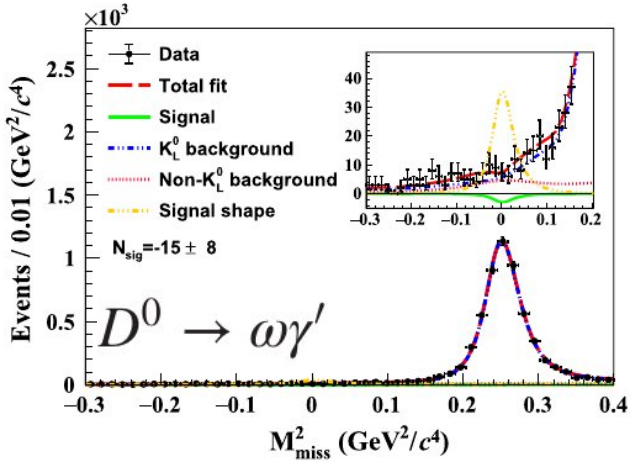
Search for a massless dark photon in $D^0 \to \omega\gamma'$ and $D^0 \to \gamma\gamma'$

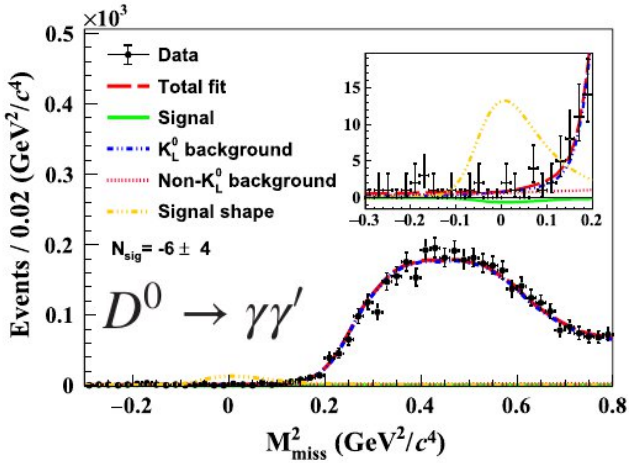


- Using 7.9 fb^{-1} data @ 3.773 GeV
- Double-tag method with $\overline{D}^0$ reconstructed in 3 hadronic decay modes
- Upper limits @ 90% CL are set for the first time:

$$\mathcal{B}(D^0 \to \omega\gamma') < 1.1 \times 10^{-5}$$

$$\mathcal{B}(D^0 \to \gamma\gamma') < 2.0 \times 10^{-6}$$





PRD 106 (2022) 072008

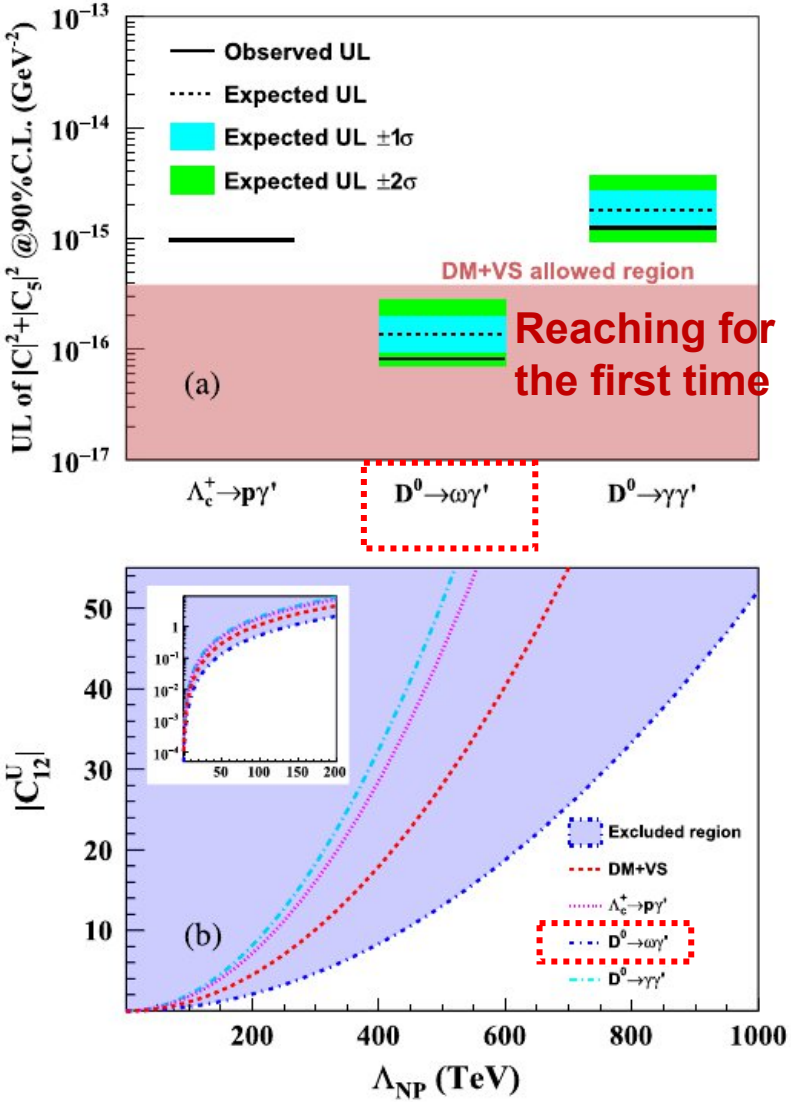
Search for a massless dark photon in $D^0 \to \omega\gamma'$ and $D^0 \to \gamma\gamma'$

- Using 7.9 fb^{-1} data @ 3.773 GeV
- Double-tag method with $\overline{D}^0$ reconstructed in 3 hadronic decay modes
- Upper limits @ 90% CL 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:

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



Prospects

White Paper
CPC 44 (2020) 040001

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

Summary

- Rare/forbidden D decays related to $c \to u$ processes offer unique opportunities for indirect NP searches
- LNV & BNV decays are useful to test different NP models
- Synergies among BESIII/BELLEII/LHCb important to narrow down on NP
- A lot of analyses still in the pipeline, stay tuned!
  - Updated searches on $D \to h(h^{(\prime)})e^+e^-$
  - Radiative $D_{(s)}$ decays
  - LFV $D_{(s)} \to hh'e\mu$ decays
  - Invisible ($D_{(s)} \to X\nu\bar{\nu}$) decays