Rare Charm Decays

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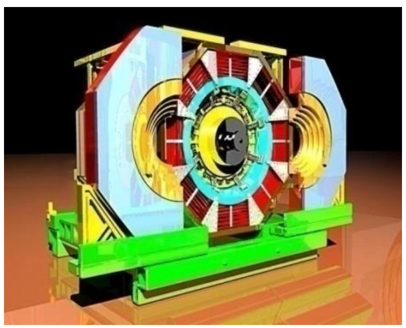


Overview

- Introduction

Rare charm decays

- Physics highlights

Flavor Changing Neutral Current

Lepton Flavor Violation

Lepton Number Violation

Baryon Number Violation

- Summary

Rare Charm Decays

- Processes:

  Standard Model is dominant (SM)

  Standard Model contribution is highly suppressed (SM + New Physics)

  Standard Model contribution is forbidden (New Physics)

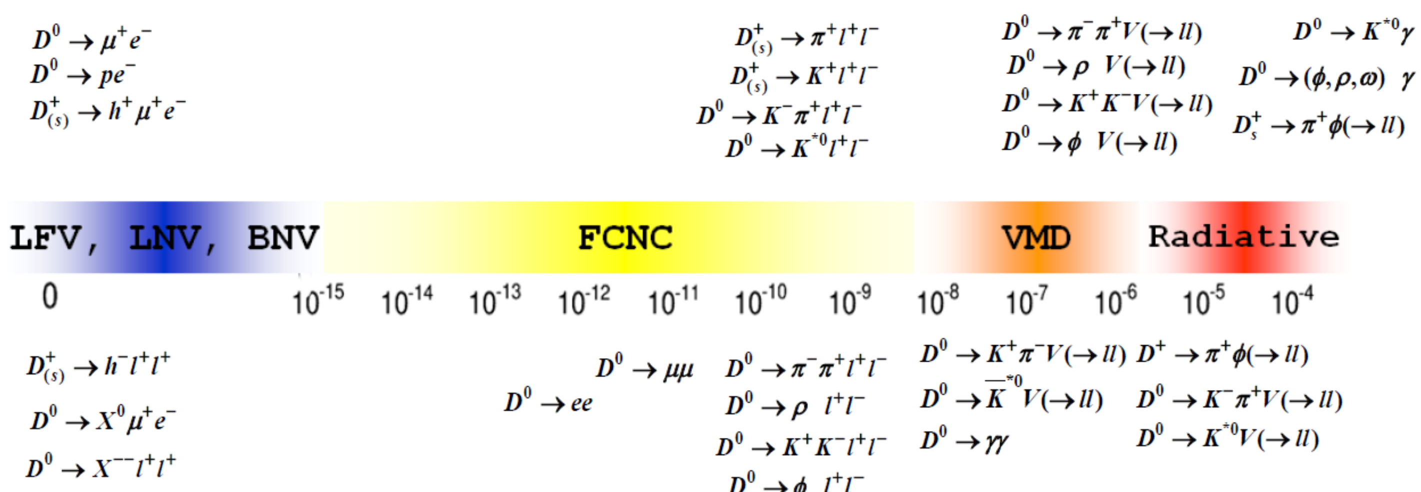
- Branching ratios of about 10^{-9} or smaller

  FCNC: Flavour Cahnging Neutral Current

  BNV: Baryon Number Violation

  LNV: Lepton Number Violation

  LFV: Lepton Flavour Violation



Rare Charm Decays

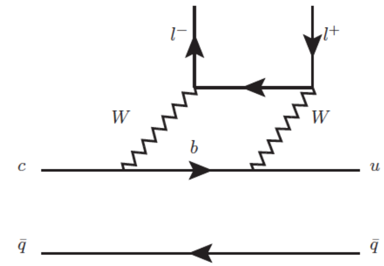
- Charm hadron: contains up-type heavy quark

  complementary information to B and K sector in NP search

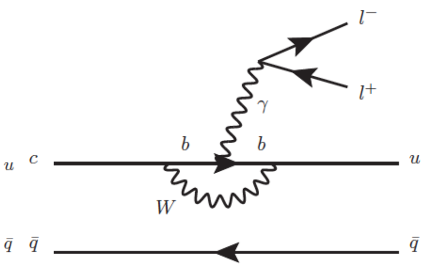
- Strong GIM mechanism in charm decays
- Constrain effects from New Physics
- Processes are forbidden at tree level in the SM, but allowed in loop and box diagrams
- Short distance contributions at one-loop level

  GIM cancellation is almost exact

  BF = O(10^{-9})



box diagram

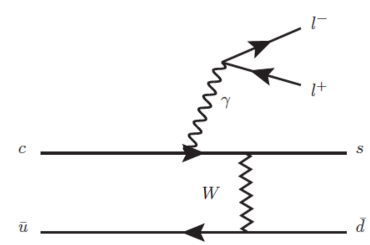


penguin diagram

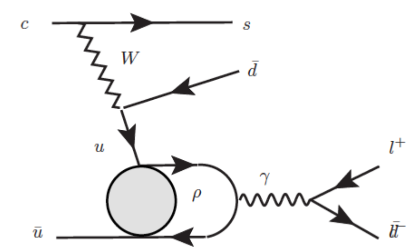
- Long distance contributions

  Vector Meson Dominance (VMD)

  BF = O(10^{-6})



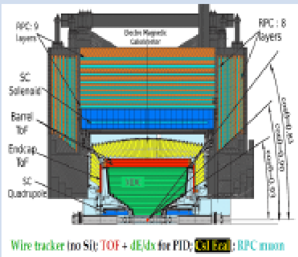
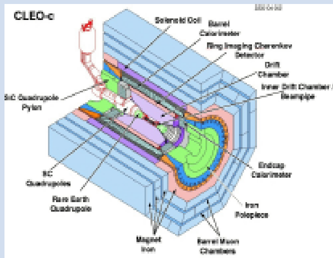
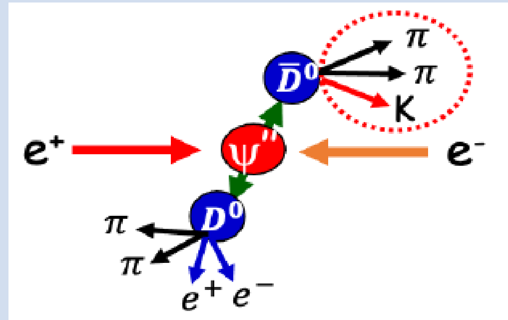
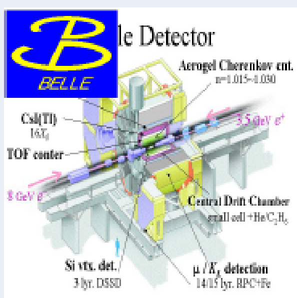
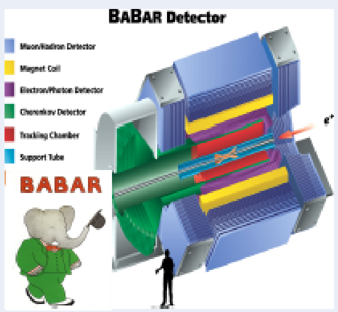
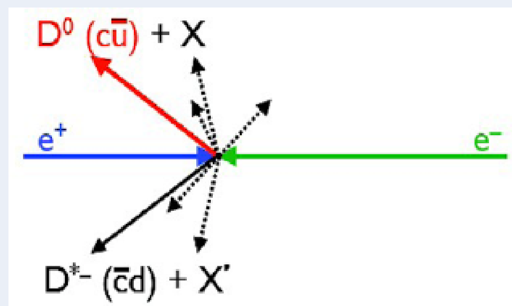
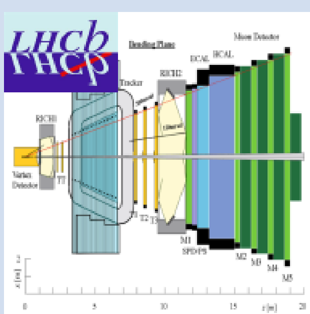
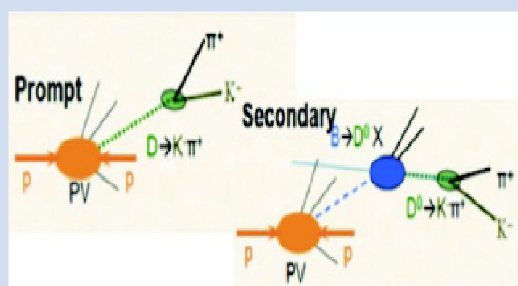
photon pole



VMD

- Away from long-distance contributions, potential for New Physics to be visible
- Test of Lepton Universality, by comparing decays to electrons *vs* muons

Experimental Scenarios

Experiments	Decay Chain	Benefit
BESIII CLEO-c  		• Extremely clean environment • DT method, almost bkg free • Quantum coherence • High trigger efficiency • Easy detection of neutrals and electrons
 		• Clean environment • High trigger efficiency • Easy detection of neutrals • Boost: time-dependent analysis
		• Large production rate • Large boost: excellent time resolution

Latest Rare Charm Decays Investigations

- Flavor Changing Neutral Current
  2019: $D^0 \to K^-\pi^+e^+e^-$ (BABAR, PRL 122, 081802)
  2021: $J/\psi \to D^-e^+\nu_e$ (BESIII, JHEP06 157)
  2021: $D^+_{(S)} \to hl^+l^-$ (LHCb, JHEP06 044)
  2021: $D^0 \to h^+h^-\mu^+\mu^-$ (LHCb, arXiv:2111.03327, submitted to PRL)
  2022: $D^0 \to \pi^0\nu\bar{\nu}$ (BESIII, PRD 105, 071102)

- Lepton Flavor Violation
  2020: $D^0 \to hh'l^+l^-$ (BABAR, PRL 124, 071802)
  2020: $D^0 \to X^0e^\pm\mu^\mp$ (BABAR, PRD 101, 112003)
  2021: $D^+_{(S)} \to he^\pm\mu^\mp$ (LHCb, JHEP06 044)

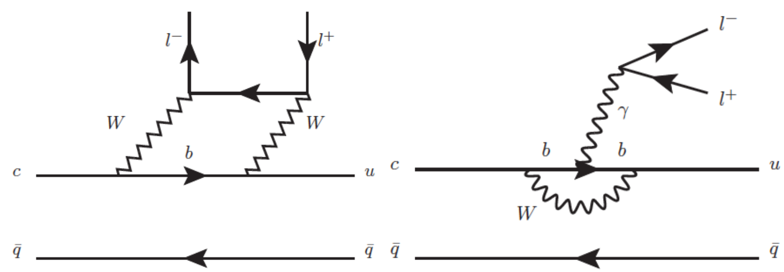
- Lepton Number Violation
  2019: $D \to K\pi e^+e^+$ (BESIII, PRD 99, 112002)
  2020: $D^0 \to hh'l^+l^+$ (BABAR, PRL 124, 071802)
  2021: $D^+_{(S)} \to hl^+l^+$ (LHCb, JHEP06 044)

- Baryon/Lepton Number Violation
  2020: $D^+ \to \bar{\Lambda}(\bar{\Sigma}^0)e^+$, $D^+ \to \Lambda(\Sigma^0)e^+$ (BESIII, PRD 101, 031102)
  2022: $D^0 \to pe^-$ + c.c. (BESIII, PRD 105, 032006)

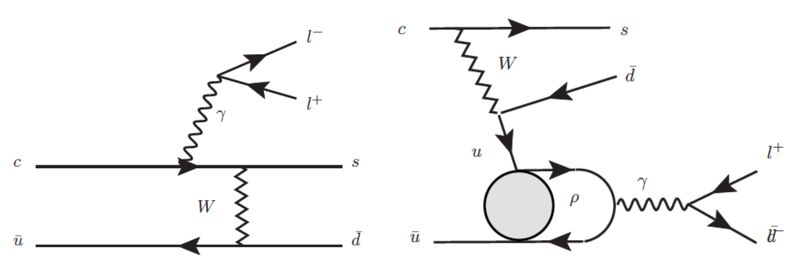
FCNC Processes

- In SM, FCNC is strongly suppressed by GIM mechanism and can happen only through loop diagram, leading to a very small BF, 10^{-9}, theoretically
- The suppression in charm decays is much stronger than those in B and K system due to stronger diagram cancellation than the down-type quarks
- However, it can reach 10^{-6} under LD contribution
- Sensitive to New Physics

SD contributions



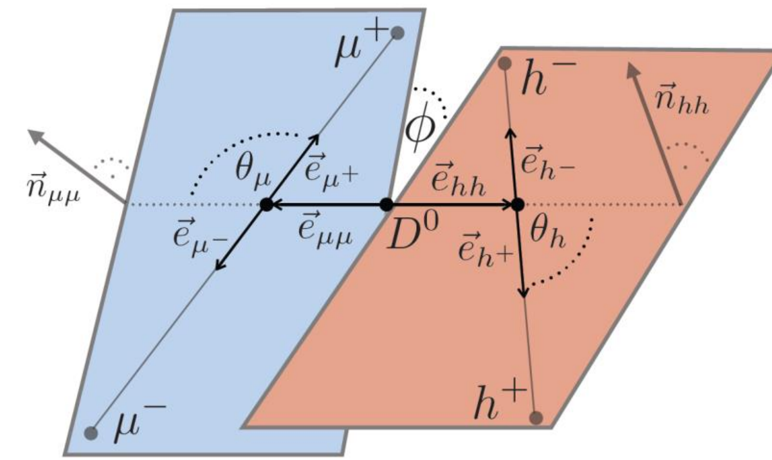
LD contributions



FCNC Processes

LHCb
arXiv:2111.03327
Submitted to PRL

$D^0 \to h^+h^-\mu^+\mu^-$



- 9 fb^{-1} at 7, 8, and 13 TeV
- $D^{*+} \to D^0\pi^+$, $D^0 \to h^+h^-\mu^+\mu^-$, $h = \pi, K$
- Decays described by:
  $q^2=m^2(\mu^+\mu^-)$, $p^2=m^2(h^+h^-)$, θ_μ, θ_h, φ
- Differential decay rate depends on 9 angular coefficients $I_{1\text{-}9}$

$$\langle I_2 \rangle = \frac{\Gamma(|\cos\theta_\mu| > 0.5) - \Gamma(|\cos\theta_\mu| < 0.5)}{\Gamma(|\cos\theta_\mu| > 0.5) + \Gamma(|\cos\theta_\mu| < 0.5)}$$

CP average $\langle S_{\rm i} \rangle = \frac{1}{2}\left[\langle I_{\rm i} \rangle + (-)\langle \overline{I}_{\rm i} \rangle\right]$

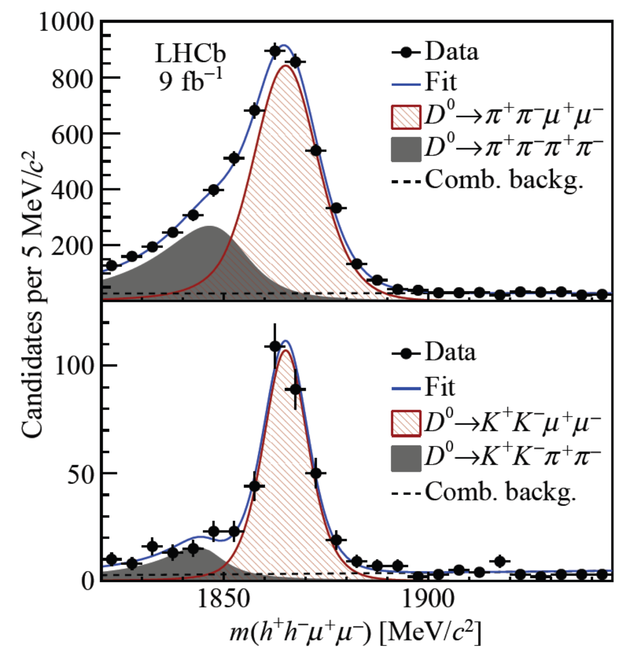
Asymmetry $\langle A_{\rm i} \rangle = \frac{1}{2}\left[\langle I_{\rm i} \rangle - (+)\langle \overline{I}_{\rm i} \rangle\right]$

- Signal: Hypatia distribution
- Background: Johnson S_U distribution + exponential

3579

Events

318



FCNC Processes

LHCb
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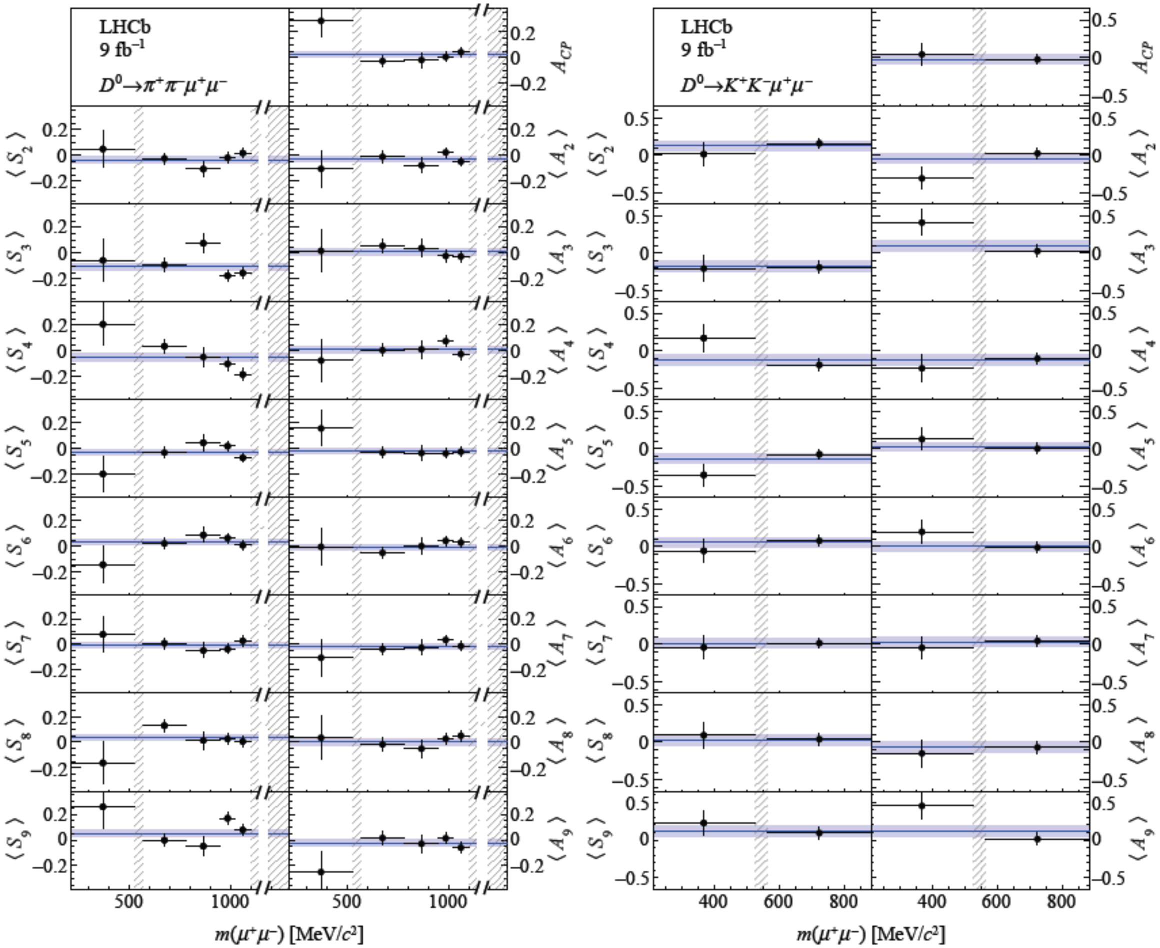
$D^0 \to h^+h^-\mu^+\mu^-$



$$\langle S_{\rm i}\rangle = \frac{1}{2}\left[\langle I_{\rm i}\rangle + (-)\langle \overline{I}_{\rm i}\rangle\right]$$

$$\langle A_{\rm i}\rangle = \frac{1}{2}\left[\langle I_{\rm i}\rangle - (+)\langle \overline{I}_{\rm i}\rangle\right]$$

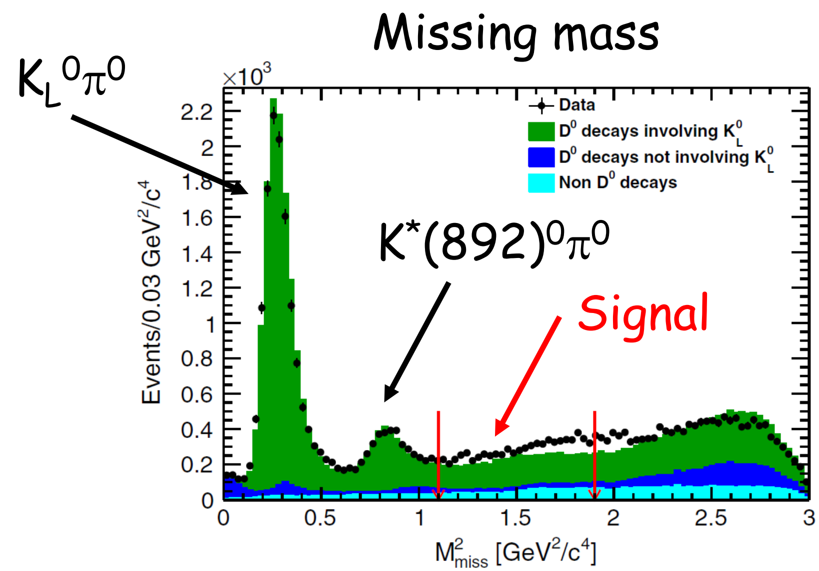
- Null-test observables: $\langle S_{5-7}\rangle$ and $\langle A_{2-9}\rangle$ in agreement with the SM null-hypothesis
- Constrain parameters of physics models
- First full angular analysis

FCNC Processes

BESIII
PRD 105 (2022) L071102

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

- 2.93 fb^{-1} @ 3,773 GeV
- Decay chain $e^+e^- \to D^0\bar{D}^0$, $D^0 \to \pi^0\nu\bar{\nu}$
  $\bar{D}^0 \to K^+\pi^-$, $K^+\pi^-\pi^0$, $K^+\pi^-\pi^-\pi^+$
- First experimental search
- No long distance contributions
- Double-Tag method
- Energy difference: $\Delta E = E_{D0bar} - E_{beam}$
  Beam constrained mass: $M_{BC} = \sqrt{E^2_{beam}/c^4 - |\vec{p}_{\bar{D}^0}|^2/c^2}$
- Branching fraction: $B_{sig} = \frac{N_{sig}}{B_{\pi^0\to\gamma\gamma}\sum_a N^a_{tag}\varepsilon^a_{tag,sig}/\varepsilon^a_{tag}}$, a indicate the tag mode
- Background: model obtained with data-driven method

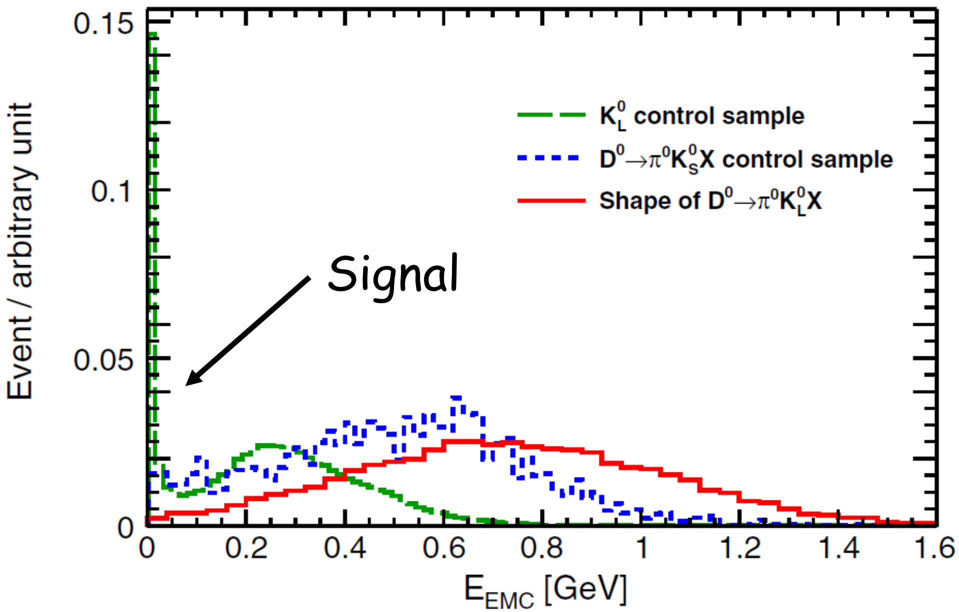


FCNC Processes

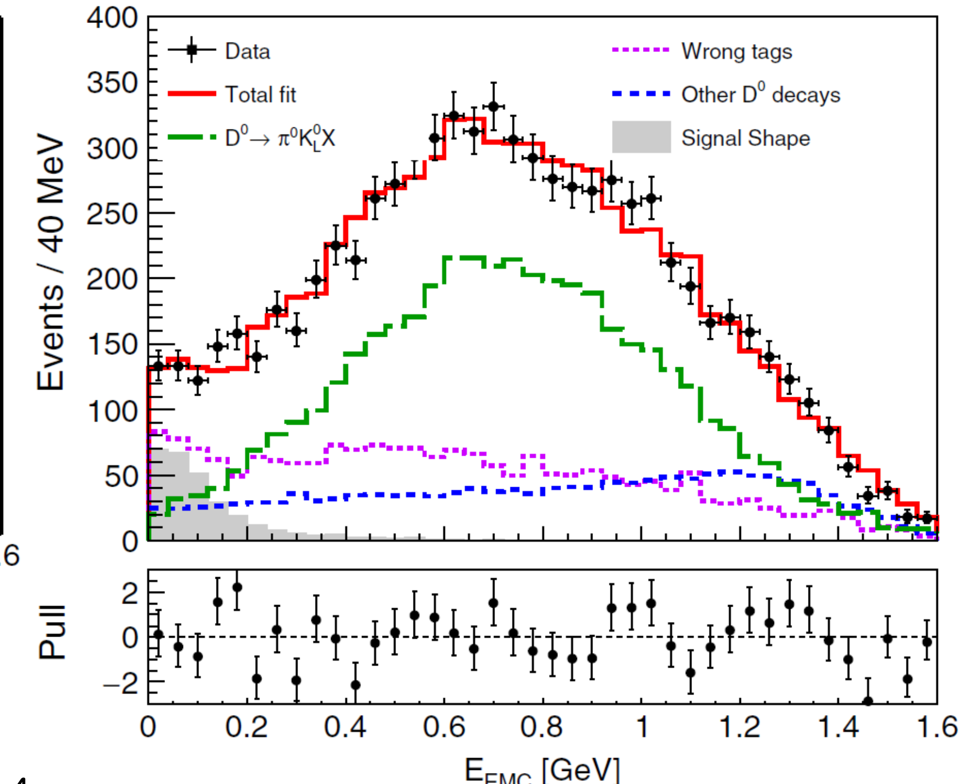
BESIII
PRD 105 (2022) L071102

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

EMC energy not associated with signal and tag decays



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



Upper limit at 90% CL: $B_{sig} = 2.1 \times 10^{-4}$

First experimental search for $D^0 \to \pi^0 \nu \bar{\nu}$

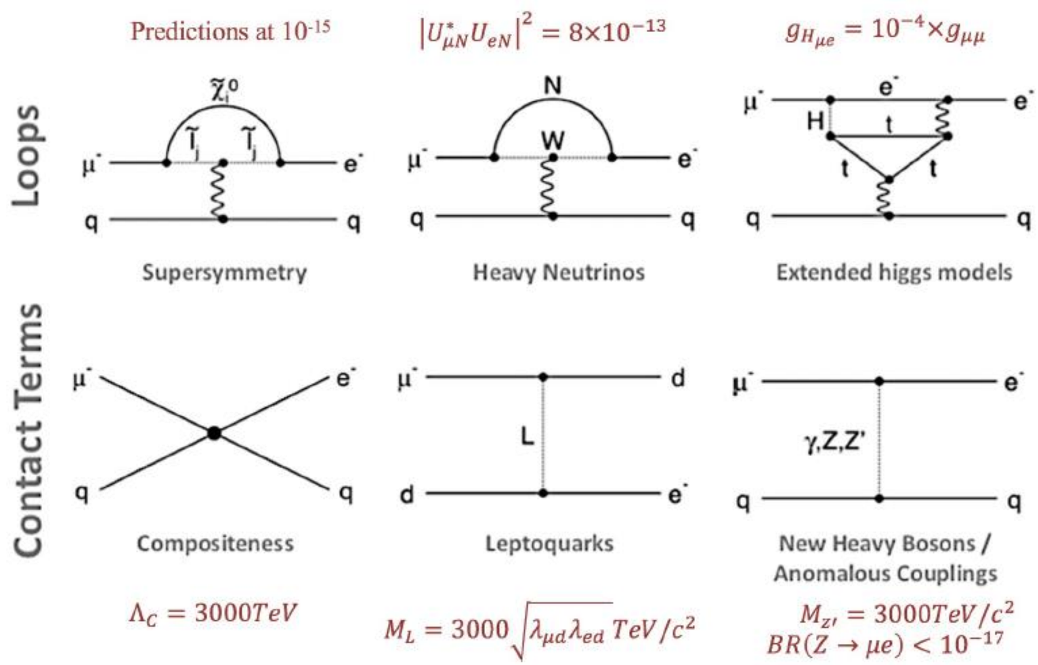
Plan to collect about 20 fb^{-1} at $\psi(3770)$

LFV Processes

• The LFV process is forbidden in SM, however, flavor non-conserving mixing among generations has been observed in neutrino oscillations.

• The smallness of neutrino masses leads to a very large suppression of the predicted branching fractions [1]. So, any significant sign of a LFV signal could indicate physics beyond the SM.

[1] L. Calibbi et al. Riv. Nuovo Cimento 41, 71 (2018)

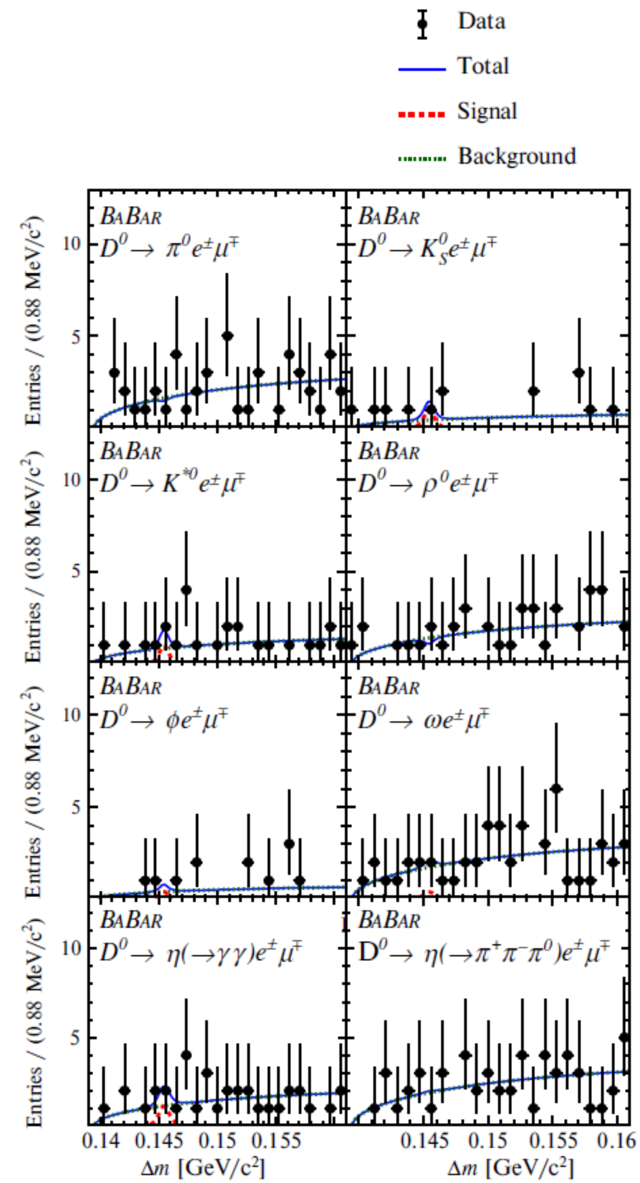


LFV Processes

BABAR
PRD 101 (2020) 112003

$D^0 \to X^0 e^{\pm}\mu^{\mp}$

- 468 fb^{-1} @ $\Upsilon(4S)$
- 39 fb^{-1} "off peak" (40 MeV below $\Upsilon(4S)$)
- Decay chain $e^+e^- \to c\bar{c}$, $D^{*+} \to D^0\pi^+$
- 8 decay modes: $D^0 \to X^0 e^{\pm}\mu^{\mp}$
  $X^0 = \pi^0, \eta, K_S^0, \rho, \omega, \varphi, K^{*0}(\to K^-\pi^+)$
- 3 normalization modes
  $D^0 \to K^-\pi^+\pi^+\pi^-$, $K^-K^+\pi^+\pi^-$, $\pi^-\pi^+\pi^+\pi^-$
- Full reconstruction of signal modes
- Maximum likelyhood fit to $\Delta m = m(D^{*+}) - m(D^0)$
- Branching fraction: $\mathcal{B}_{sig} = \frac{N_{sig}}{N_{norm}} \frac{\epsilon_{norm}}{\epsilon_{sig}} \frac{\mathcal{L}_{norm}}{\mathcal{L}_{sig}} \frac{\mathcal{B}_{norm}}{\mathcal{B}(X^0)}$
- Signal: Cruijff function,
  φ mode: 2 asymmetric-sigma Gaussian
  Background: Argus function



LFV Processes

BABAR
PRD 101 (2020) 112003

$D^0 \to X^0 e^\pm \mu^\mp$

- No signal found
- Upper limits calculated at 90% confidence level using Feldman-Cousins method
- 1-2 order of magnitude more stringent constraints

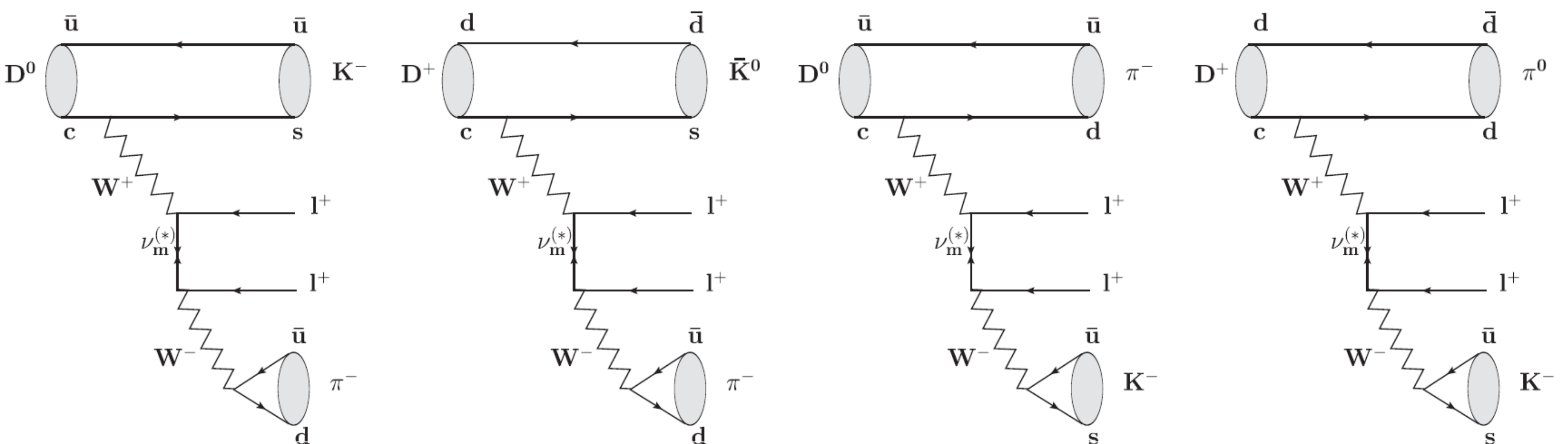
Decay mode	N_{sig} (candidates)	ϵ_{sig} (%)	$\mathcal{B}$ ($\times 10^{-7}$)	$\mathcal{B}$ 90% U.L. ($\times 10^{-7}$) BABAR	Previous
$D^0 \to \pi^0 e^\pm \mu^\mp$	$-0.3 \pm 2.0 \pm 0.9$	2.15 ± 0.03	$-0.6 \pm 4.8 \pm 2.2$	8.0	860
$D^0 \to K^0_S e^\pm \mu^\mp$	$0.7 \pm 1.7 \pm 0.7$	3.01 ± 0.04	$1.9 \pm 4.6 \pm 1.9$	8.7	500
$D^0 \to \bar{K}^{*0} e^\pm \mu^\mp$	$0.8 \pm 1.8 \pm 0.8$	2.31 ± 0.03	$2.8 \pm 6.1 \pm 2.6$	12.5	830
$D^0 \to \rho^0 e^\pm \mu^\mp$	$-0.7 \pm 1.7 \pm 0.4$	2.10 ± 0.03	$-1.8 \pm 4.4 \pm 1.0$	5.0	490
$D^0 \to \phi e^\pm \mu^\mp$	$0.0 \pm 1.4 \pm 0.3$	3.43 ± 0.04	$0.1 \pm 3.8 \pm 0.9$	5.1	340
$D^0 \to \omega e^\pm \mu^\mp$	$0.4 \pm 2.3 \pm 0.5$	1.46 ± 0.03	$1.8 \pm 9.5 \pm 1.9$	17.1	1200
$D^0 \to \eta e^\pm \mu^\mp$			$6.1 \pm 9.7 \pm 2.3$	22.5	1000
with $\eta \to \gamma\gamma$	$1.6 \pm 2.3 \pm 0.5$	2.96 ± 0.04	$7.0 \pm 10.5 \pm 2.4$	24.0	
with $\eta \to \pi^+\pi^-\pi^0$	$0.0 \pm 2.8 \pm 0.7$	2.46 ± 0.04	$0.4 \pm 25.8 \pm 6.0$	43.0	

LNV Processes

- Lepton number (LN) is conserved in the Standard Model.
- Neutrino oscillation $\rightarrow m_\nu \neq 0 \rightarrow$ New Physics scenario.
- Nature of neutrino: Majorana or Dirac?
- Majorana neutrino can violate LN by two unit
- LNV is introduced in many New Physics models

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

Dirac Majorana



(a) $D^0 \rightarrow K^-\pi^-l^+l^+$ (CF) (b) $D^+ \rightarrow \bar{K}^0\pi^-l^+l^+$ (CF) (c) $D^0 \rightarrow K^-\pi^-l^+l^+$ (DCS) (d) $D^+ \rightarrow K^-\pi^0l^+l^+$ (DCS)

LNV Processes

BESIII
PRD 99 (2019) 112002

$D \to K\pi e^+e^+$

2.93 fb^{-1} @ 3.773 GeV

Single-Tag analysis

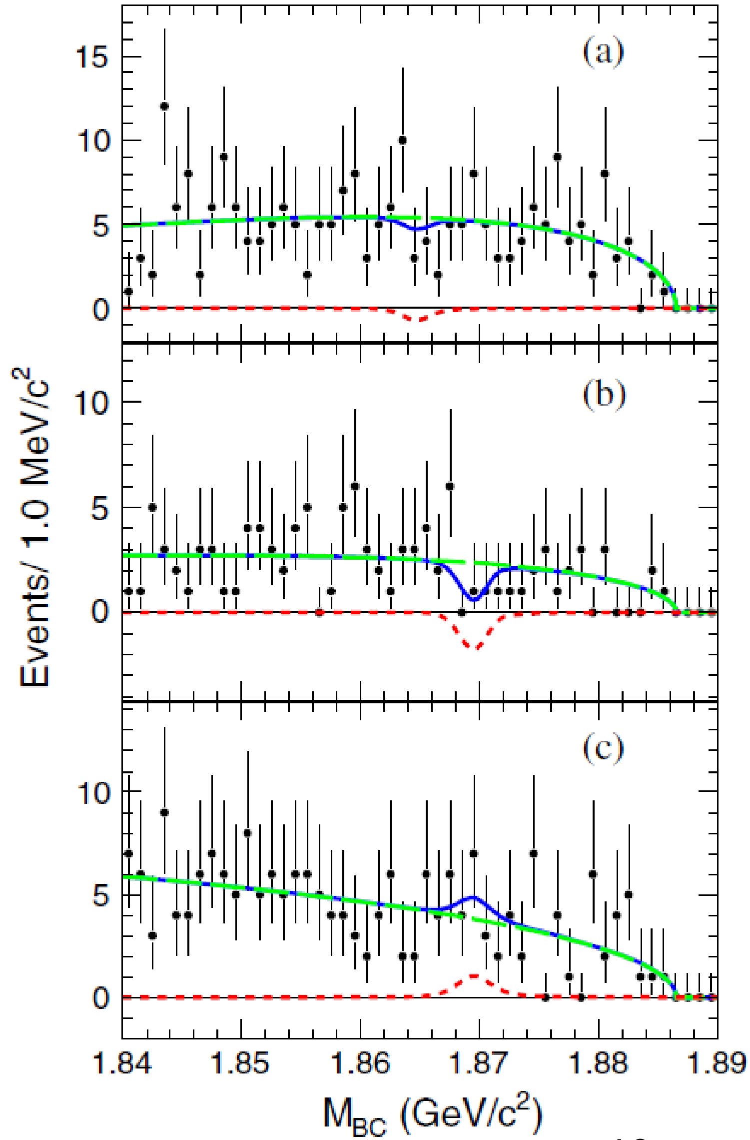
3 channels investigated

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

Requirements on ΔE to suppress background

Branching fraction:

$$\mathcal{B}_{D\to K\pi e^+e^+} = \frac{N_{\rm sig}}{2 \cdot N^{\rm tot}_{D\bar{D}} \cdot \epsilon \cdot \mathcal{B}}$$



Channels investigated	UL @ 90% CL
$D^0 \to K^-\pi^-e^+e^+$	<2.8x10^{-6}
$D^+ \to K^0_S\pi^-e^+e^+$	<3.3x10^{-6}
$D^+ \to K^-\pi^0e^+e^+$	<8.5x10^{-6}

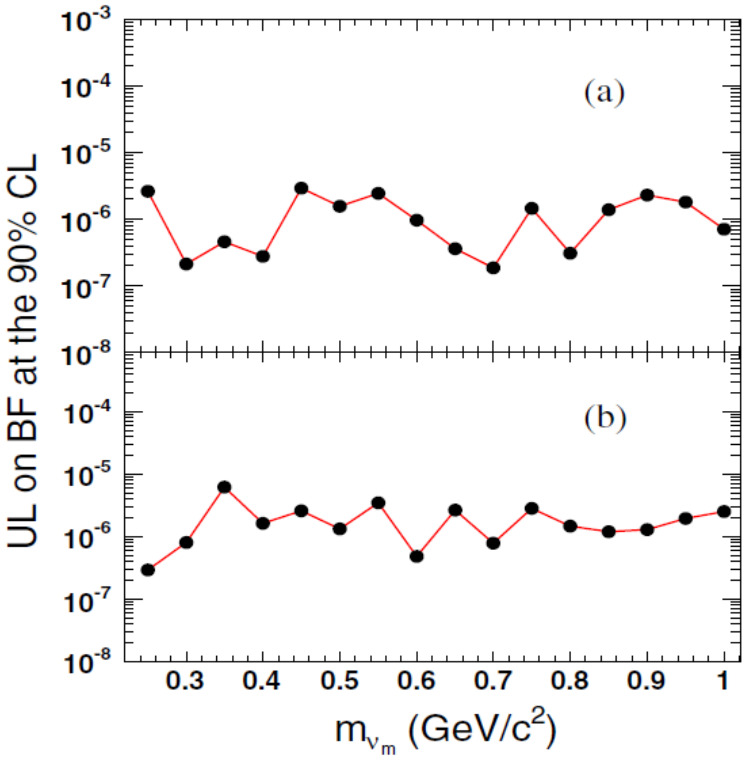
First searches

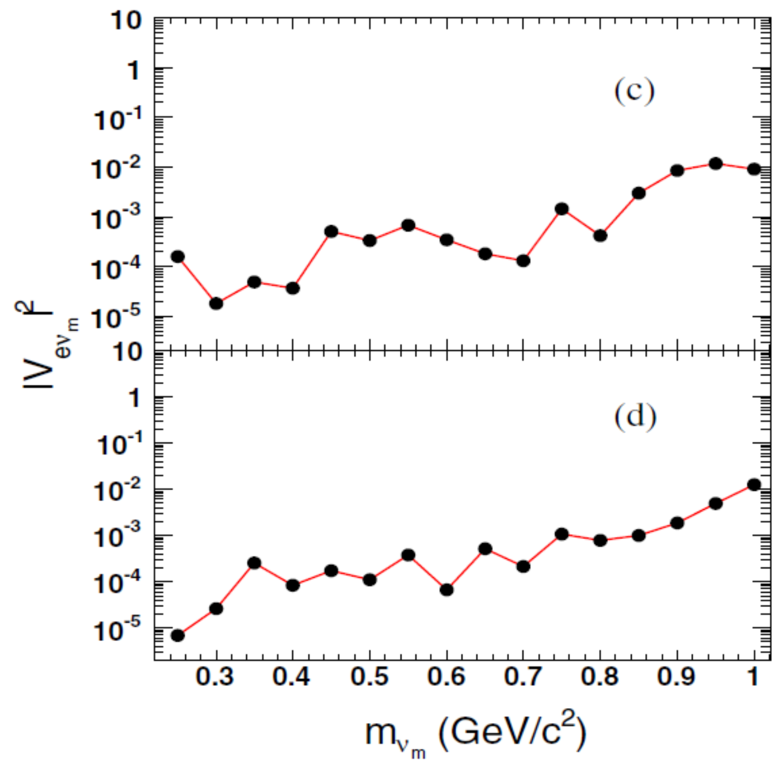
LNV Processes

BESIII
PRD 99 (2019) 112002

$D \to K\pi e^+e^+$

Search for Majorana neutrino





Different m_ν hypothesis tested

between 0.25 and 1 GeV/c^2

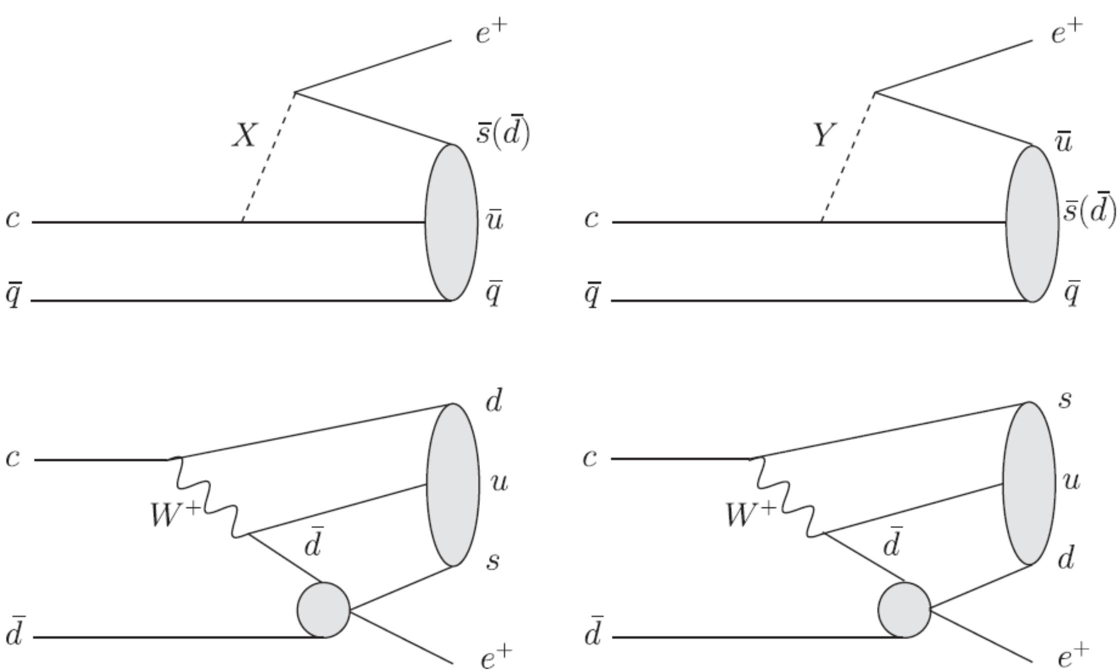
BF related to mixing matrix elements

$$\frac{\Gamma(m_{\nu_m}, V_{e\nu_m}(m_{\nu_m}))}{\Gamma(m_{\nu_m}, V'_{e\nu_m}(m_{\nu_m}))} = \frac{|V_{e\nu_m}(m_{\nu_m})|^4}{|V'_{e\nu_m}(m_{\nu_m})|^4}$$

[Chin. Phys. C 39, 013101 (2015)]

BNV & LNV Processes

- Asymmetry of matter and anti-matter
- Universe evolution
- BNV: even a small amount would have major consequences on the universe and its evolution.
- BNV is allowed in GUTs and SM extensions
- Prediction of B($D^+ \to (\bar{\Lambda} l^+)$) is no more than 10^{-29} (PRD72, 095001)



SM extension:

under six operators

$\Delta(B\text{-}L) = 0$

under seven operators

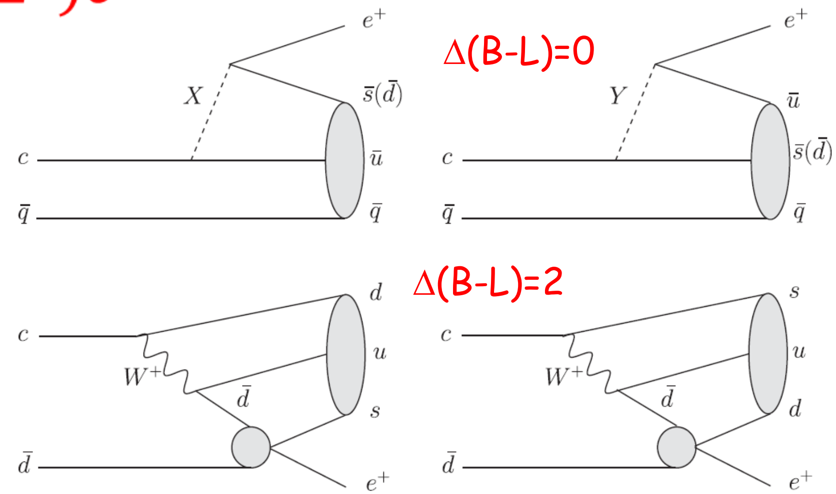
$\Delta(B\text{-}L) = 2$

BNV-LNV Processes

BESIII
PRD 101 (2020) 031102

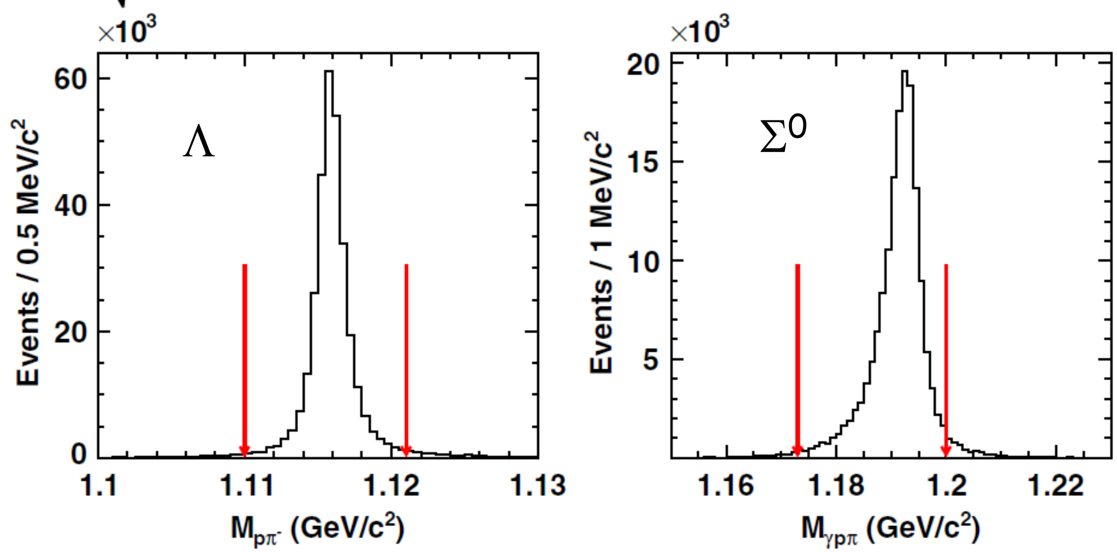
$D^+ \to \bar{\Lambda}(\bar{\Sigma}^0)e^+$

- 2.93 fb^{-1} @ 3,773 GeV
- Decay chain $e^+e^- \to D^+D^-$ (8×10^6 events)
  $D^+ \to \bar{\Lambda}(\bar{\Sigma}^0)e^+$, $D^+ \to \Lambda(\Sigma^0)e^+$
  $\Lambda \to p\pi^-$, $\Sigma^0 \to \gamma\Lambda$
- First measurement
- Energy difference: $\Delta E = E_D - E_{beam}$
  Beam constrained mass: $M_{BC} = \sqrt{E_{beam}^2 - \vec{p}_D^{\,2}}$



MC simulations

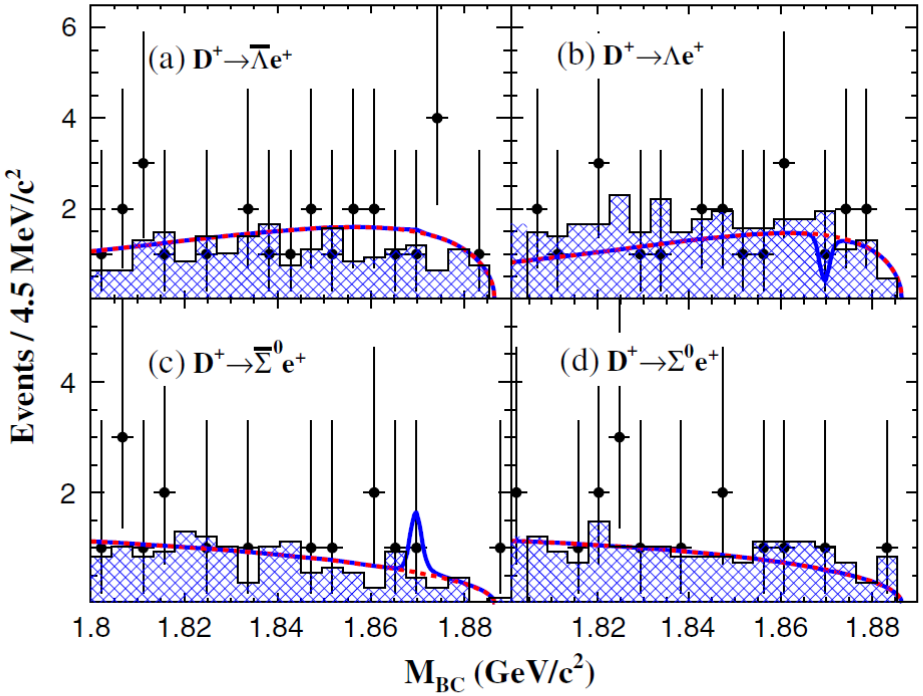
Σ^0 asymmetric selection



BNV-LNV Processes

BESIII
PRD 101 (2020) 031102

$D^+ \to \bar{\Lambda}(\bar{\Sigma}^0)e^+$



Signal: MC shape + Gaussian

Background: ARGUS function

Branching fraction

$$B^{UL} = N^{UL}_{sig}/(2 \cdot N^{tot}_{D^+D^-} \cdot \varepsilon \cdot B_{\Lambda,\Sigma^0})$$

First measurement

Mode	$N^{\rm UL}_{\rm sig}$	ε (%)	$\mathcal{B}^{\rm UL}$
Λe^+	5.6	31.11 ± 0.14	1.1×10^{-6}
$\bar{\Lambda} e^+$	3.4	31.18 ± 0.10	6.5×10^{-7}
$\Sigma^0 e^+$	4.5	16.31 ± 0.07	1.7×10^{-6}
$\bar{\Sigma}^0 e^+$	3.5	16.40 ± 0.07	1.3×10^{-6}

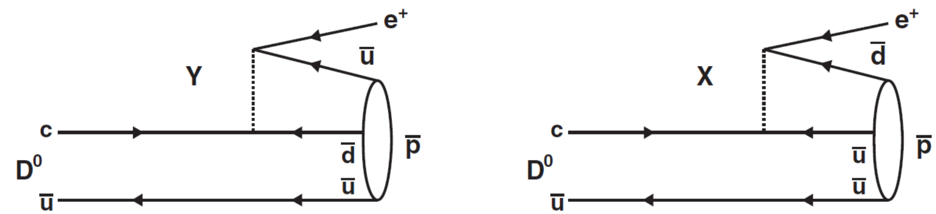
BNV-LNV Processes

BESIII
PRD 105 (2022) 032006

$D^0 \to pe^-$

- 2.93 fb^{-1} @ 3,773 GeV

- Decay chain $e^+e^- \to \bar{D}^0 D^0$, $D^0 \to pe^-$+c.c.
  $\bar{D}^0 \to K^+\pi^-$, $K^+\pi^-\pi^0$, $K^+\pi^-\pi^-\pi^+$



- X and Y heavy hypothetical gauge bosons

production mechanism

- Double-Tag method

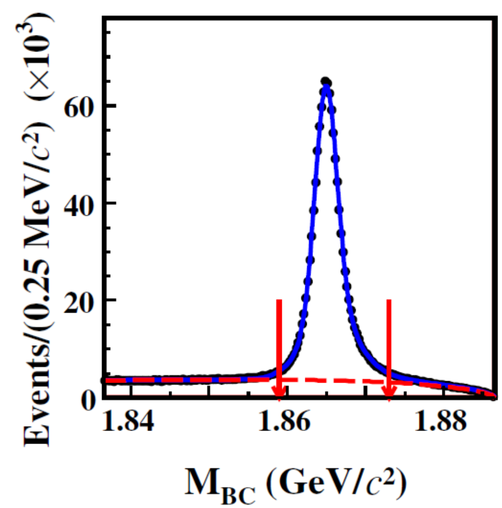
- Full reconstruction of signal modes

- Energy difference: $\Delta E = E_{D0bar} - E_{beam}$
  Beam constrained mass: $M_{BC} = \sqrt{E_{beam}^2/c^4 - |\vec{p}_{\bar{D}^0}|^2/c^2}$

- Branching fraction: $B_{sig} = \frac{N_{DT}}{N_{ST}\varepsilon_{sig}}$

- Signal: MC shape + double Gaussian
  Background: Argus function

Single-Tag fit



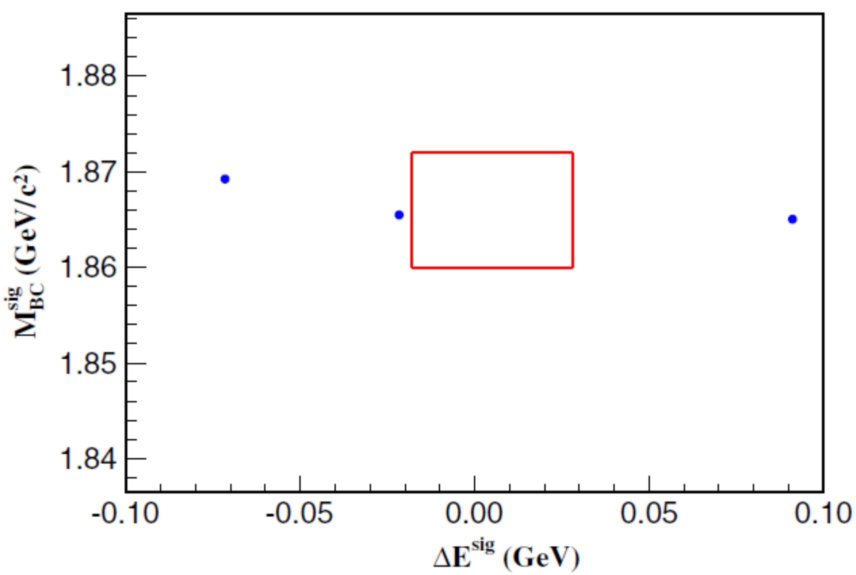
$\bar{D}^0 \to K^+\pi^-\pi^0$

BNV-LNV Processes

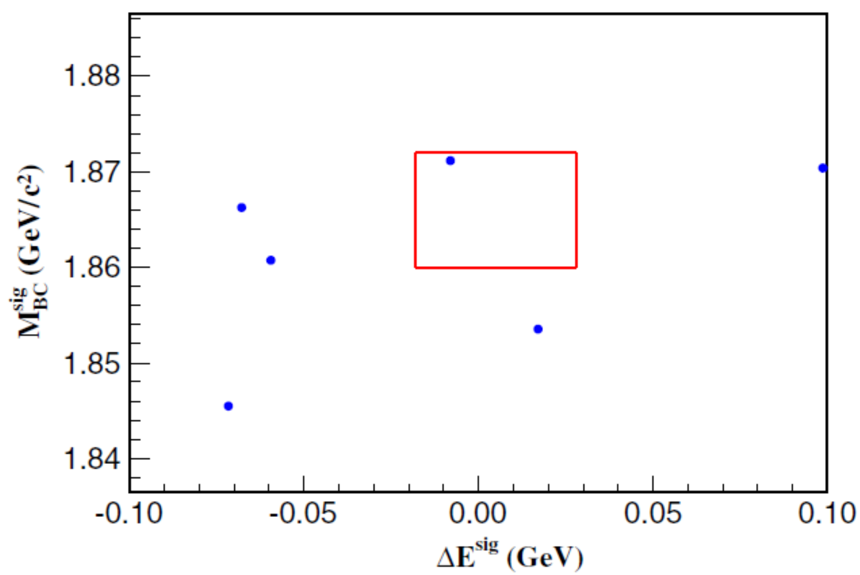
BESIII
PRD 105 (2022) 032006

D^0 -> pe^-

- Asymmetric shapes from MC studies
- No obvious signal observed
- Upper limits $B_{D^0\to\bar{p}e^+} < 1.2 \bullet 10^{-6}$ and $B_{D^0\to pe^-} < 2.2 \bullet 10^{-6}$
- Most stringent constraints, but far from predictions



$D^0 \to \bar{p}e^+$



$D^0 \to pe^-$

FCNC-LFV-LNV Processes

LHCb
JHEP06 (2021) 044

$D^+_{(S)}$ -> hll

- 1.6 fb^{-1}, 2016 dataset (8 TeV)
- 25 charm decays
- SM allowed decays involve FCNC or weak annihilation
- Forbidden in SM at tree level and CKM suppressed
- Dominated by LD tree level contributions
- Regions dominated by resonances in dilepton mass are vetoed when fitting

FCNC

$D^+_{(S)} \to \pi^+ e^+ e^-$
$D^+_{(S)} \to \pi^+ \mu^+ \mu^-$
$D^+_{(S)} \to K^+ e^+ e^-$
$D^+_{(S)} \to K^+ \mu^+ \mu^-$

Resonance dominated

$D^+_{(S)} \to \pi^+ \varphi(\mu^+ \mu^-)$
$D^+_{(S)} \to K^+ \varphi(e^+ e^-)$

LFV, LFV & LNV

$D^+_{(S)} \to \pi^+ \mu^\pm e^\mp$
$D^+_{(S)} \to K^+ \mu^\pm e^\mp$

$D^+ \to K^- \mu^+ e^+$
$D^+_{(S)} \to \pi^- \mu^+ e^+$
$D^+_{(S)} \to \pi^- e^+ e^+$
$D^+_{(S)} \to \pi^- \mu^+ \mu^+$
$D^+ \to K^- e^+ e^+$
$D^+ \to K^- \mu^+ \mu^+$

FCNC-LFV-LNV Processes

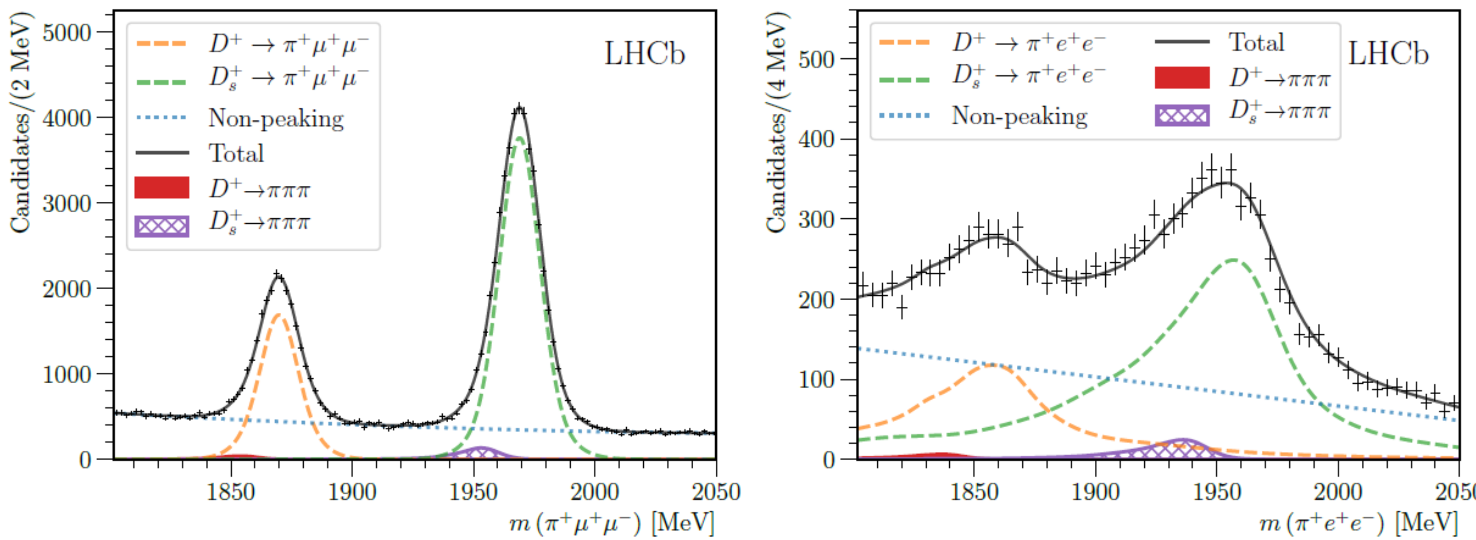
LHCb
JHEP06 (2021) 044

$D^+_{(S)}$ -> hll

Normalization with $D^+_{(S)} \to \pi^+ \varphi(l^+ l^-)$

Signal: double Gaussian

Background: exponential (muons) or third order Chebyshev polynomial (electrons)



Channel	$\mathcal{B}$ [2]	Fitted yield
$D^+ \to (\phi \to \mu^-\mu^+)\ \pi^+$	$(1.63 \pm 0.12) \times 10^{-6}$	$18\,100 \pm 340$
$D^+ \to (\phi \to e^-e^+)\ \pi^+$	$(1.67 \pm 0.07) \times 10^{-6}$	2160 ± 180
$D_s^+ \to (\phi \to \mu^-\mu^+)\ \pi^+$	$(1.33 \pm 0.10) \times 10^{-5}$	$42\,000 \pm 400$
$D_s^+ \to (\phi \to e^-e^+)\ \pi^+$	$(1.37 \pm 0.05) \times 10^{-5}$	5320 ± 180

FCNC-LFV-LNV Processes

LHCb
JHEP06 (2021) 044

Results consistent with background only hypothesis

World's best limits for 23 decays

$D^+_{(S)}$ -> hll

Decay	Branching fraction upper limit $[10^{-9}]$				Improvement	
	D^+		D_s^+			
	90 % CL	95 % CL	90 % CL	95 % CL	D^+	D_s^+
$D^+_{(s)} \to \pi^+\mu^+\mu^-$	67	74	180	210	1.1	2.3
$D^+_{(s)} \to \pi^-\mu^+\mu^+$	14	16	86	96	1.6	1.4
$D^+_{(s)} \to K^+\mu^+\mu^-$	54	61	140	160	79.0	150.0
$D^+_{(s)} \to K^-\mu^+\mu^+$	-	-	26	30	-	500.0
$D^+_{(s)} \to \pi^+e^+\mu^-$	210	230	1100	1200	14.0	11.0
$D^+_{(s)} \to \pi^+\mu^+e^-$	220	220	940	1100	16.0	21.0
$D^+_{(s)} \to \pi^-\mu^+e^+$	130	150	630	710	16.0	13.0
$D^+_{(s)} \to K^+e^+\mu^-$	75	83	790	880	16.0	18.0
$D^+_{(s)} \to K^+\mu^+e^-$	100	110	560	640	28.0	17.0
$D^+_{(s)} \to K^-\mu^+e^+$	-	-	260	320	-	23.0
$D^+_{(s)} \to \pi^+e^+e^-$	1600	1800	5500	6400	0.7	2.3
$D^+_{(s)} \to \pi^-e^+e^+$	530	600	1400	1600	2.1	3.0
$D^+_{(s)} \to K^+e^+e^-$	850	1000	4900	5500	1.2	0.8
$D^+_{(s)} \to K^-e^+e^+$	-	-	770	840	-	6.7

LNV-LFV Processes

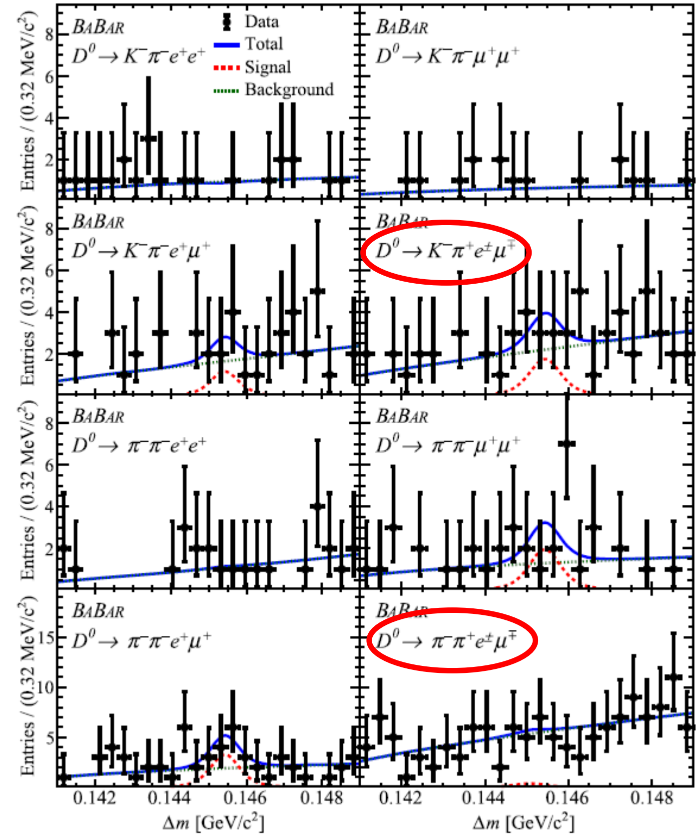
BABAR
PRL 124 (2020) 071802

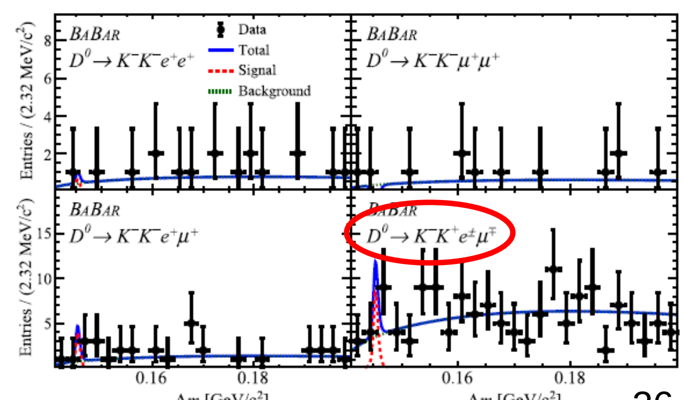
$D^0 \to hhll$

- 468 fb^{-1} @ $\Upsilon(4S)$
- 39 fb^{-1} "off peak" (40 MeV below $\Upsilon(4S)$)
- Decay chain $e^+e^- \to c\bar{c}$, $D^{*+} \to D^0\pi^+$
- 12 decay modes: $D^0 \to hh'l^+l^+$, $hh'l^+l^-$
  h and h' = K or π

LFV

- 3 normalization modes
  $D^0 \to K^-\pi^+\pi^+\pi^-$, $K^-K^+\pi^+\pi^-$, $\pi^-\pi^+\pi^+\pi^-$
- Full reconstruction of signal modes
- Maximum likelyhood fit to $\Delta m = m(D^{*+}) - m(D^0)$
- Branching fraction: $$\mathcal{B}_{\rm sig} = \frac{N_{\rm sig}}{N_{\rm norm}} \frac{\epsilon_{\rm norm}}{\epsilon_{\rm sig}} \frac{\mathcal{L}_{\rm norm}}{\mathcal{L}_{\rm sig}} \mathcal{B}_{\rm norm}$$
- Signal: Cruijff function
  Background: Argus function





LNV-LFV Processes

BABAR
PRL 124 (2020) 071802

D^0 -> hhll

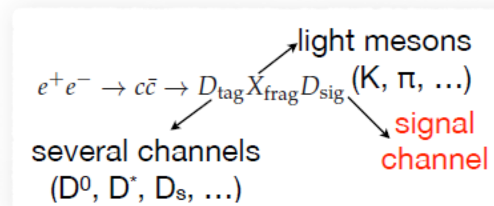
- No signal found
- Upper limits calculated at 90% confidence level using Feldman-Cousins method
- 1-3 order of magnitude more stringent constraints

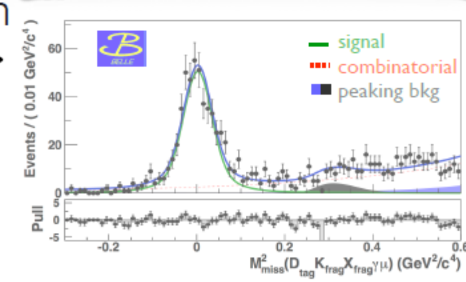
Decay mode $D^0 \to$	N_{sig} (candidates)	ϵ_{sig} (%)	$\mathcal{B}$ ($\times 10^{-7}$)	$\mathcal{B}$ 90% U.L. ($\times 10^{-7}$) BABAR	Previous
$\pi^-\pi^-e^+e^+$	$0.22 \pm 3.15 \pm 0.54$	4.38 ± 0.05	$0.27 \pm 3.90 \pm 0.67$	9.1	1120
$\pi^-\pi^-\mu^+\mu^+$	$6.69 \pm 4.88 \pm 0.80$	4.91 ± 0.05	$7.40 \pm 5.40 \pm 0.91$	15.2	290
$\pi^-\pi^-e^+\mu^+$	$12.42 \pm 5.30 \pm 1.45$	4.38 ± 0.05	$15.41 \pm 6.59 \pm 1.85$	30.6	790
$\pi^-\pi^+e^\pm\mu^\mp$	$1.37 \pm 6.15 \pm 1.28$	4.79 ± 0.06	$1.55 \pm 6.97 \pm 1.45$	17.1	150
$K^-\pi^-e^+e^+$	$-0.23 \pm 0.97 \pm 1.28$	3.19 ± 0.05	$-0.38 \pm 1.60 \pm 2.11$	5.0	28 [21]
$K^-\pi^-\mu^+\mu^+$	$-0.03 \pm 2.10 \pm 0.40$	3.30 ± 0.05	$-0.05 \pm 3.34 \pm 0.64$	5.3	3900
$K^-\pi^-e^+\mu^+$	$3.87 \pm 3.96 \pm 2.36$	3.48 ± 0.04	$5.84 \pm 5.97 \pm 3.56$	21.0	2180
$K^-\pi^+e^\pm\mu^\mp$	$2.52 \pm 4.60 \pm 1.35$	3.65 ± 0.05	$3.62 \pm 6.61 \pm 1.95$	19.0	5530
$K^-K^-e^+e^+$	$0.30 \pm 1.08 \pm 0.41$	3.25 ± 0.04	$0.43 \pm 1.54 \pm 0.58$	3.4	1520
$K^-K^-\mu^+\mu^+$	$-1.09 \pm 1.29 \pm 0.42$	6.21 ± 0.06	$-0.81 \pm 0.96 \pm 0.32$	1.0	940
$K^-K^-e^+\mu^+$	$1.93 \pm 1.92 \pm 0.83$	4.63 ± 0.05	$1.93 \pm 1.93 \pm 0.84$	5.8	570
$K^-K^+e^\pm\mu^\mp$	$4.09 \pm 3.00 \pm 1.59$	4.83 ± 0.05	$3.93 \pm 2.89 \pm 1.45$	10.0	1800

Search for Rare Charm Decays at *Belle II*

Belle II will search for rare or forbidden charm decays, especially those with *neutrals* or *missing energy* in the final state, for example:

- $D^0 \to \gamma\gamma$, $c \to u$ FCNC *unique to Belle II*
  - current UL $\mathscr{B}(D^0 \to \gamma\gamma) < 8.5 \times 10^{-7}$ at 90% CL (Belle, PRD 93 051102) is 2 orders of magnitudes higher than SM predictions (PRD 64 074008, PRD 66 014009)
  - estimated UL at *Belle II* $\mathscr{B}(D^0 \to \gamma\gamma) < 1.5 \times 10^{-7}$ at 90% CL (with 50 ab-1)
- $D \to h\nu\bar{\nu}$, $\Lambda_c^+ \to p\nu\bar{\nu}$, strongly GIM-suppressed in the SM
  - powerful reconstruction method: reconstruct the partner charm hadron + fragmentation particles, and then use energy-momentum conservation to determine the invariant mass of the rest (Belle, PRD 95 011102) ⟶
  - can be used with *any* type of missing energy (neutrinos, dark matter, axions, other non-SM particles)





BESIII Prospects

White Paper
CPC 44 (2020) 040001

10^{-6} (Upper limit) | 10^{-6} (BESIII Expected)

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	201		1.7

20 fb^{-1} @ 3.773 GeV

6 fb^{-1}@ 4.18 GeV

Summary

- Rare decays are a great tool for New Physics studies

- Rare charm decays
  up-type quark dynamics
  complementary to strange and beauty results

- Limits are still above SM predictions

- New Physics effects have not been found yet

- New results expected from BESIII, BelleII, LHCb, and *Super Tau-Charm Factories*