Search for Lepton Number Violation decays at BESIII

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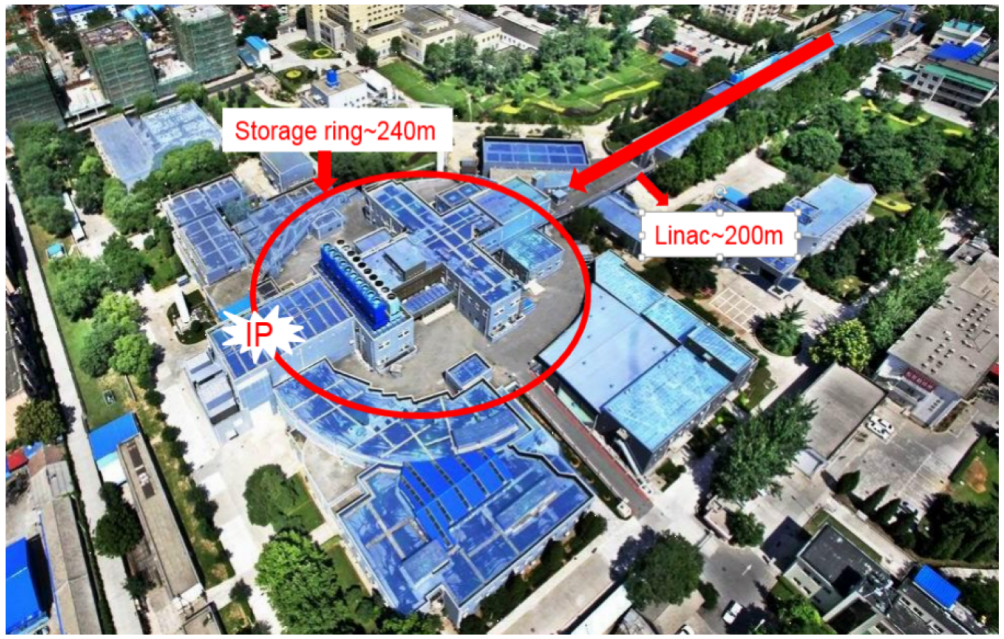
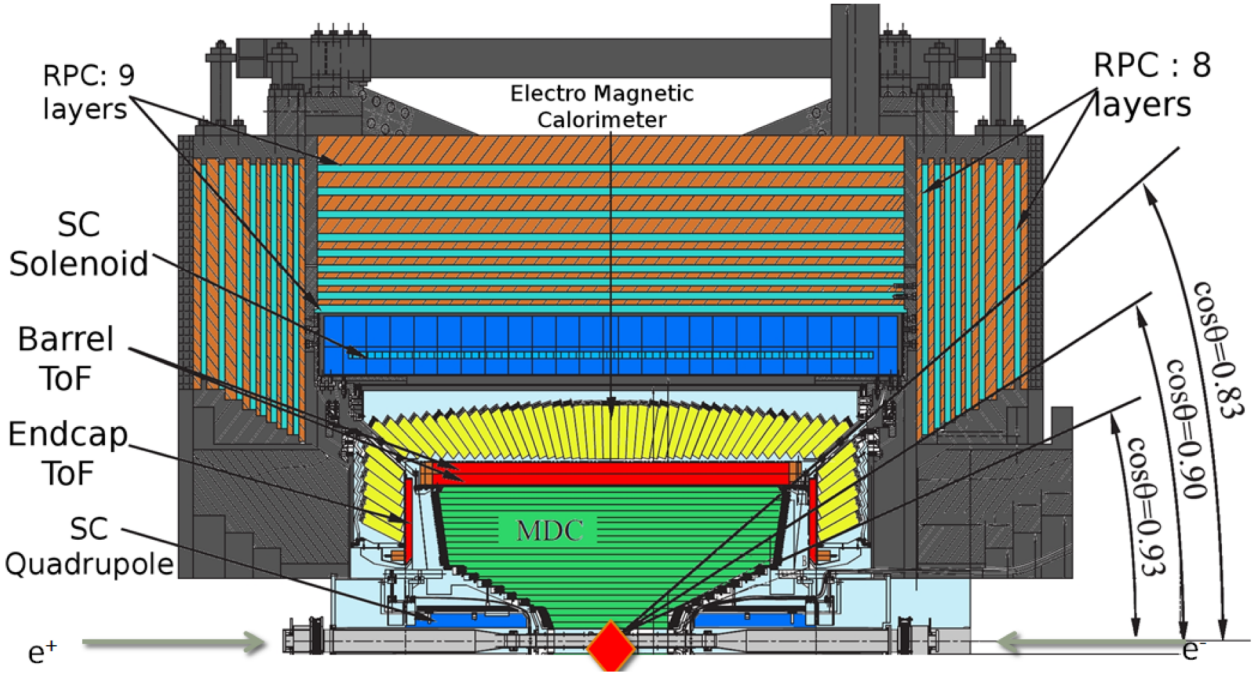
@NPG Workshop 2024, 28th Aug, Hangzhou Institute for Advanced Study, Hangzhou

Outline

01 BEPCII/BESIII





- E_{cm} : $\sqrt{s} = (2.0 - 4.95)$ GeV
- Designed luminosity (L):
- 1.00×10^{33} $cm^{-2}s^{-1}$ @ 3.89 GeV
- In 2022, L reach 1.1times of the designed L

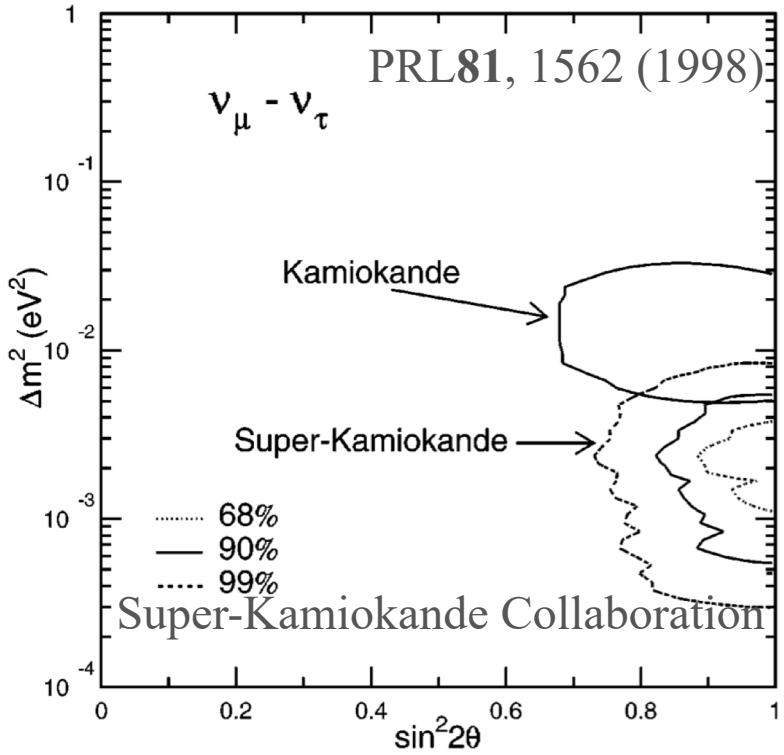
- MDC: $\sigma_p/p = 0.5\%$@ 1 GeV, $\sigma_{dE/dx} = 6\%$
- TOF: $\sigma_T = 68(110)$ ps for barrel (edncap); end cap TOF was upgraded in 2015→ 60 ps
- EMC: $\sigma_E/E = 2.5\%(5\%)$ ps for barrel (edncap)

In the future, E_{cm} will be updated to 4.95-5.6 GeV and the L will increase by 2-3 times

Implications of an observation of LNV

- In the Standard Model lepton number violation (LNV) is forbidden → Global $U(1)_L$ symmetry
- Massless neutrinos: $U(1)_e \times U(1)_\mu \times U(1)_\tau$ is automatic global symmetry

✓ Neutrino oscillation



$m_\nu \neq 0$

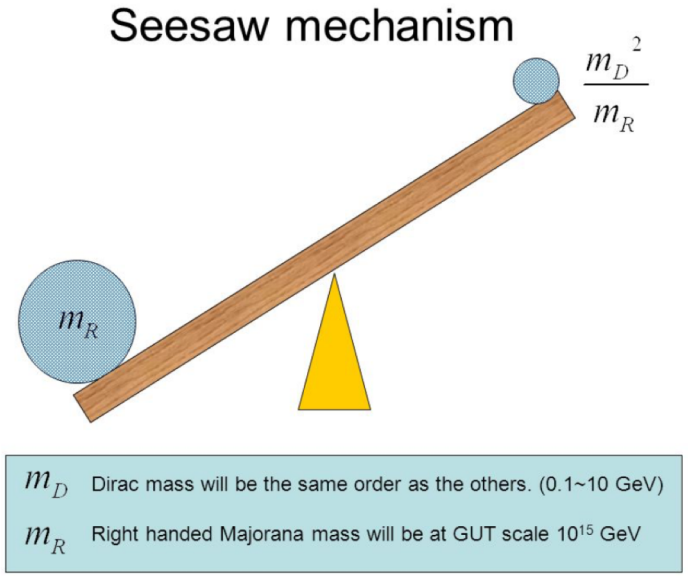
LNV process

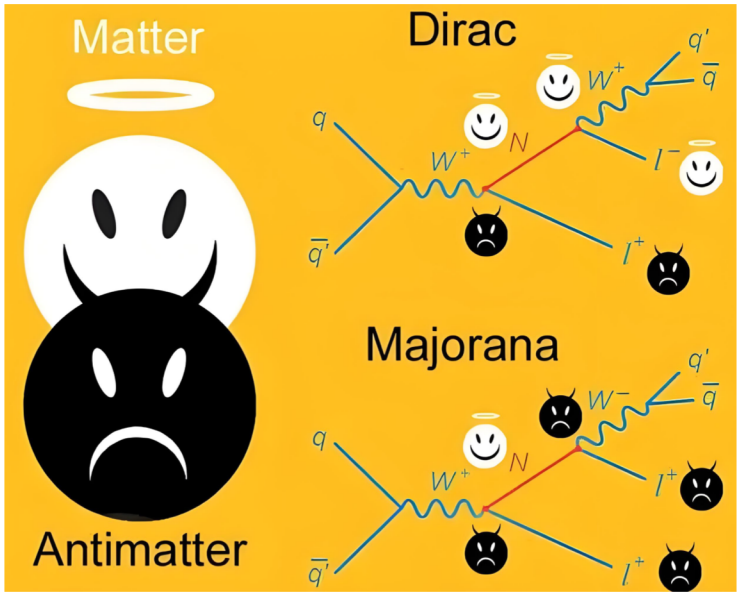
- ✓ 4th quark generation — PRD 93 094026 (2016)
- ✓ SO(10) SUSY GUT — JHEP 08 068 (2011)
- ✓ Exotic Higgs… — PRD 51 6542 (1995), PLB 93 389 (1980)

New Physics!

Open problem: Dirac or Majoranoa?

- Theoretically, "seesaw" mechanism lead model to accommodate the neutrino masses
- The mass of an observed light neutrino is given by: $m_\nu \sim y_\nu^2 v^2 / m_{\nu_m}$





Not identical

Identical

- Majorana neutrino can be manifested through the LNV decays by $\Delta L = 2$
- Different $\Delta L = 2$ processes at low and high energies have been proposed

[JHEP09,030;PRD87, 077901;CPC39,013101 (2015);PRD98, 096994;Front. Phys. 12,121201]

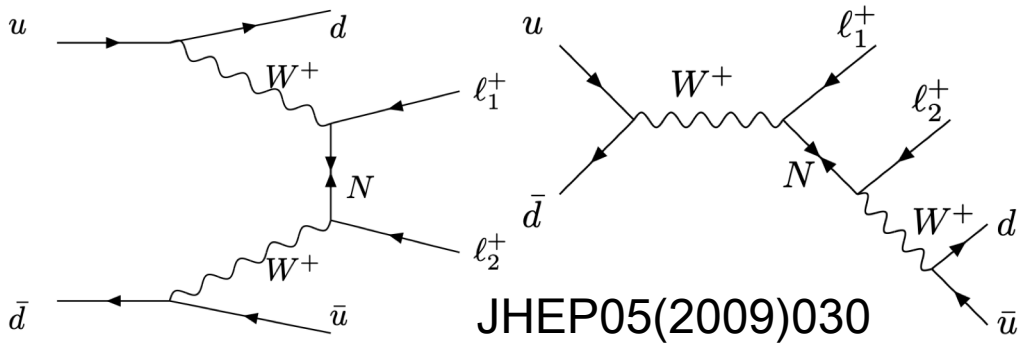
Most promising way: $0\nu\beta\beta$ decay

- Only limits on its rates have been obtained

Nucleus ($Q_{\beta\beta}$, kev)	M·t, kg·yr	FWHM, keV	BI, c/kev·kg·yr	BI·FWHM, c/kg·yr	$T_{1/2}$, yr (90% C.L.)	$\langle m_\nu \rangle$, meV	Experiment, Detector
^{76}Ge (2039.0)	127.2 (110.7)	2.6–4.9	5.2×10^{-4}	$\sim 1.8 \times 10^{-3}$	$>1.8 \times 10^{26}$	<79–180	GERDA [27], HPGe
	73.3 (64.5)	2.52	6.6×10^{-3}	16.6×10^{-3} (a)	$>8.3 \times 10^{25}$	<113–269	Majorana [25], HPGe
^{136}Xe (2457.8)	~34,000 (b) (970)	~247	$\sim 2 \times 10^{-6}$ ($\sim 7 \times 10^{-5}$)	$\sim 5 \times 10^{-4}$ ($\sim 1.7 \times 10^{-2}$)	$>2.3 \times 10^{26}$	<36–156	KamLAND-Zen [24], Xe in liquid scintillator
	290.4 (234.1)	66.4	1.8×10^{-3}	0.12	$>3.5 \times 10^{25}$	<93–286	EXO-200 [28], liquid Xe TPC
^{130}Te (2527.5)	1038.4 (288.8)	7.8	1.5×10^{-2}	0.12	$>2.2 \times 10^{25}$	<90–305	CUORE [29], LTB TeO_2
^{128}Te (866.7)	309.33 (78.56)	4.3	1.4	6.0	$>3.6 \times 10^{24}$	-	CUORE [30], LTB TeO_2
^{82}Se (2997.9)	9.94 (5.29)	20	3.5×10^{-3}	7×10^{-2}	$>4.6 \times 10^{24}$	<263–545	CUPID-0 [31], LTB ZnSe
	5.90 (4.90)	~250	$\sim 4 \times 10^{-3}$	~1	$>2.5 \times 10^{23}$	<1200–3000	NEMO-3 [26], tracking detector
^{100}Mo (3 034.4)	2.71 (1.47)	7.4	4.7×10^{-3}	3.5×10^{-2}	$>1.8 \times 10^{24}$	<280–490	CUPID-Mo [32], LTB Li_2MoO_4
^{116}Cd (2813.5)	4.68 (1.22)	170	0.15	25	$>2.2 \times 10^{23}$	<1000–1700	AURORA [37], $CdWO_4$ scintillator
^{48}Ca (4268.0)	~108 (~0.12)	241	10^{-3}	0.24	$>5.6 \times 10^{22}$ (c)	<2900–16,000	CANDLES-III [23], CaF_2 scintillation crystals

Allowing bounds to be set on the effective Majorana mass at: 10^{-1} eV

- Exchanging a single Majorana neutrino (on shell) with a mass on the order of the heavy flavor mass scale



JHEP05(2009)030

CPC39,013101 (2015)

$$\mathcal{L}=-\frac{g}{\sqrt{2}}W_{\mu}^{+}\sum_{l=e}^{\tau}V_{lN}^{*}\overline{N^{c}}\gamma^{\mu}P_{L}l+h.c.$$

- N: Mass eigenstate
- V_{lN}: Mixing matrix between the charged lepton ℓ neutrino ν_{ℓ} and heavy Majorana neutrino

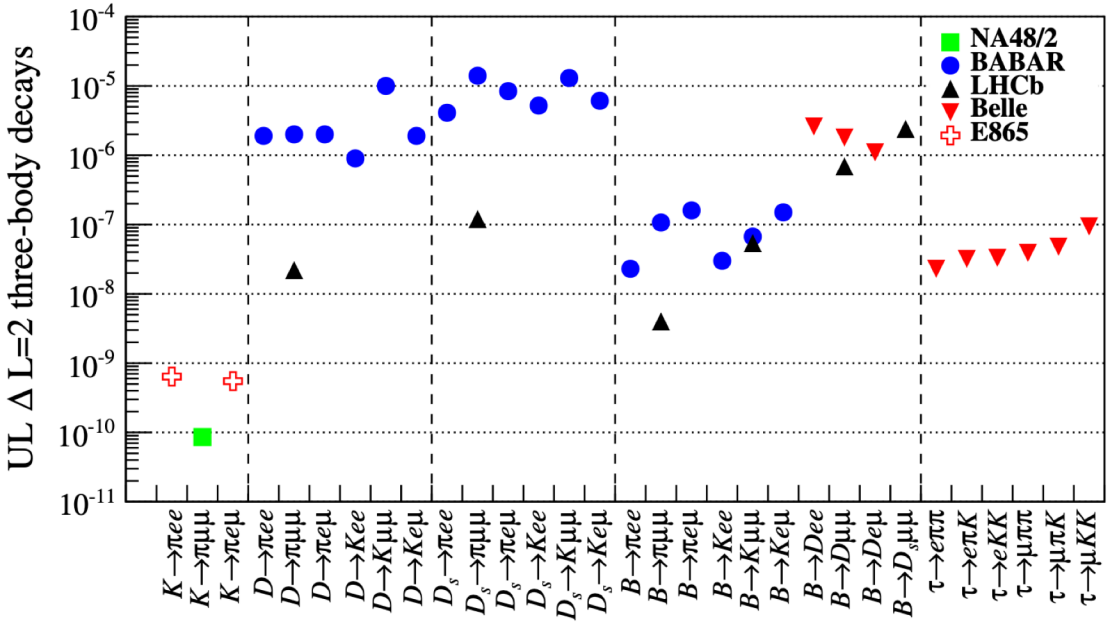
$|V_{eN}|^2<3\times10^{-3}$, $|V_{\mu N}|^2<3\times10^{-3}$, $|V_{\tau N}|^2<6\times10^{-3}$

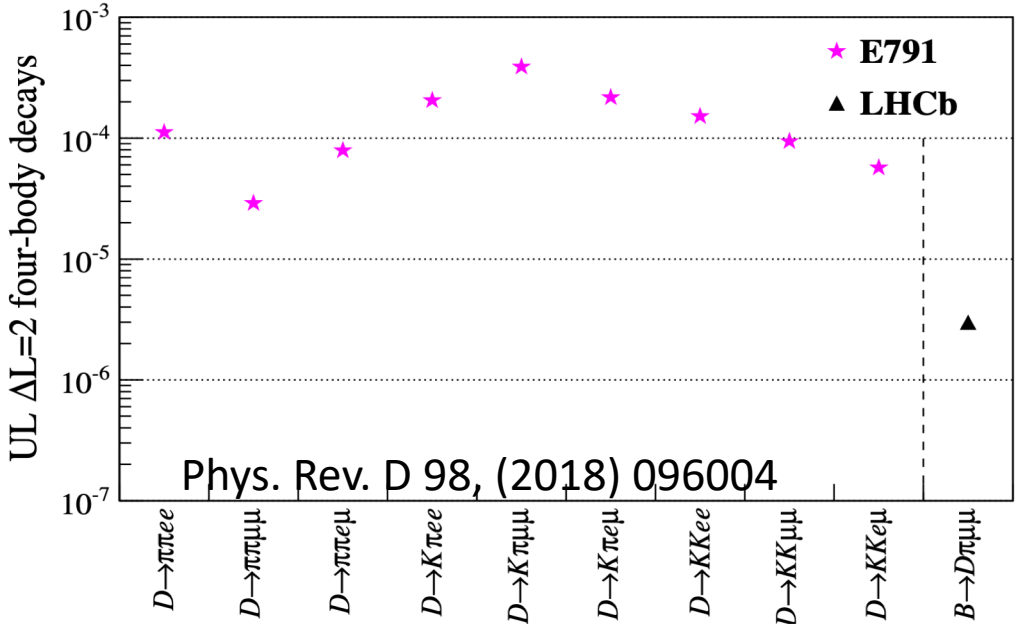
Phys. Rev. D, 2008, 78: 013010

$D^0\to K^-e^+e^+\pi^-$				$D^0\to K^-\mu^+\mu^+\pi^-$			
m_N	Γ/Γ_{tot}	m_N	Γ/Γ_{tot}	m_N	Γ/Γ_{tot}	m_N	Γ/Γ_{tot}
150	4.5×10^{-10}	600	4.0×10^{-11}	150	–	600	9.0×10^{-10}
200	6.7×10^{-10}	650	2.8×10^{-11}	200	–	650	5.9×10^{-10}
250	4.7×10^{-10}	700	2.0×10^{-11}	250	1.6×10^{-9}	700	3.8×10^{-10}
300	2.9×10^{-10}	750	1.4×10^{-11}	300	1.7×10^{-9}	750	2.3×10^{-10}
350	2.0×10^{-10}	800	9.5×10^{-12}	350	5.4×10^{-10}	800	1.4×10^{-10}
400	1.3×10^{-10}	850	6.1×10^{-12}	400	5.0×10^{-9}	850	7.7×10^{-11}
450	1.0×10^{-10}	900	3.5×10^{-12}	450	3.3×10^{-9}	900	3.6×10^{-11}
500	7.5×10^{-11}	950	1.9×10^{-12}	500	2.2×10^{-9}	950	1.7×10^{-11}
550	5.4×10^{-11}	1000	9.4×10^{-13}	550	1.4×10^{-9}	1000	7.4×10^{-12}

$D^+\to \bar{K}^0e^+e^+\pi^-$				$D^+\to \bar{K}^0\mu^+\mu^+\pi^-$			
m_N	Γ/Γ_{tot}	m_N	Γ/Γ_{tot}	m_N	Γ/Γ_{tot}	m_N	Γ/Γ_{tot}
150	1.1×10^{-9}	600	1.0×10^{-10}	150	–	600	2.3×10^{-9}
200	1.7×10^{-9}	650	7.2×10^{-11}	200	–	650	1.5×10^{-9}
250	1.2×10^{-9}	700	5.1×10^{-11}	250	4.1×10^{-9}	700	9.8×10^{-10}
300	7.3×10^{-10}	750	3.7×10^{-11}	300	4.2×10^{-9}	750	5.9×10^{-10}
350	5.1×10^{-10}	800	2.4×10^{-11}	350	1.4×10^{-9}	800	3.6×10^{-10}
400	3.3×10^{-10}	850	1.6×10^{-11}	400	1.3×10^{-8}	850	2.0×10^{-10}
450	2.6×10^{-10}	900	9.1×10^{-12}	450	8.5×10^{-9}	900	9.3×10^{-11}
500	1.9×10^{-10}	950	4.8×10^{-12}	500	5.5×10^{-9}	950	4.4×10^{-11}
550	1.4×10^{-10}	1000	2.4×10^{-12}	550	3.5×10^{-9}	1000	1.9×10^{-11}

Current experimental UL on branching ratios of $\Delta L = 2$ decays





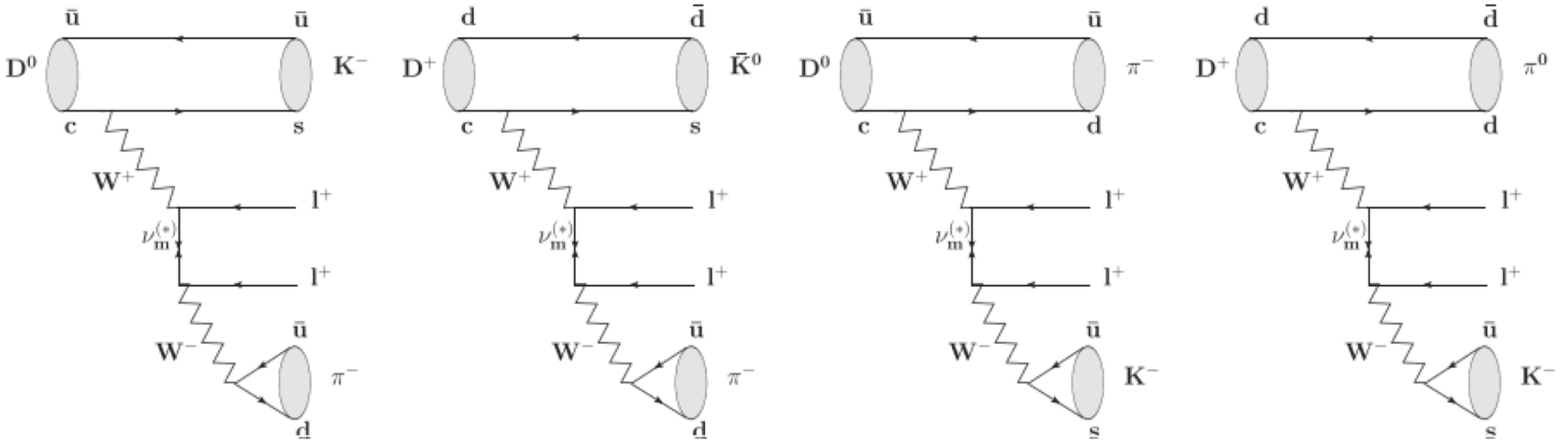
- Neutrino with mass in the range 100 MeV/c^2 to a few GeV/c^2 have been widely searched
- LHCb searched in 2021: ULs of BFs ($D_{(s)} \to hhee$) around $10^{-8} - 10^{-6}$

Up to 2018, no experimental results came from BESIII

03 LNV: $D \to K\pi e^+e^+$

Phys. Rev. D 99, (2019) 11, 112002

- Data: 2.93 fb^{-1}data taken @3.773 GeV
- Single-tag method → larger data sample

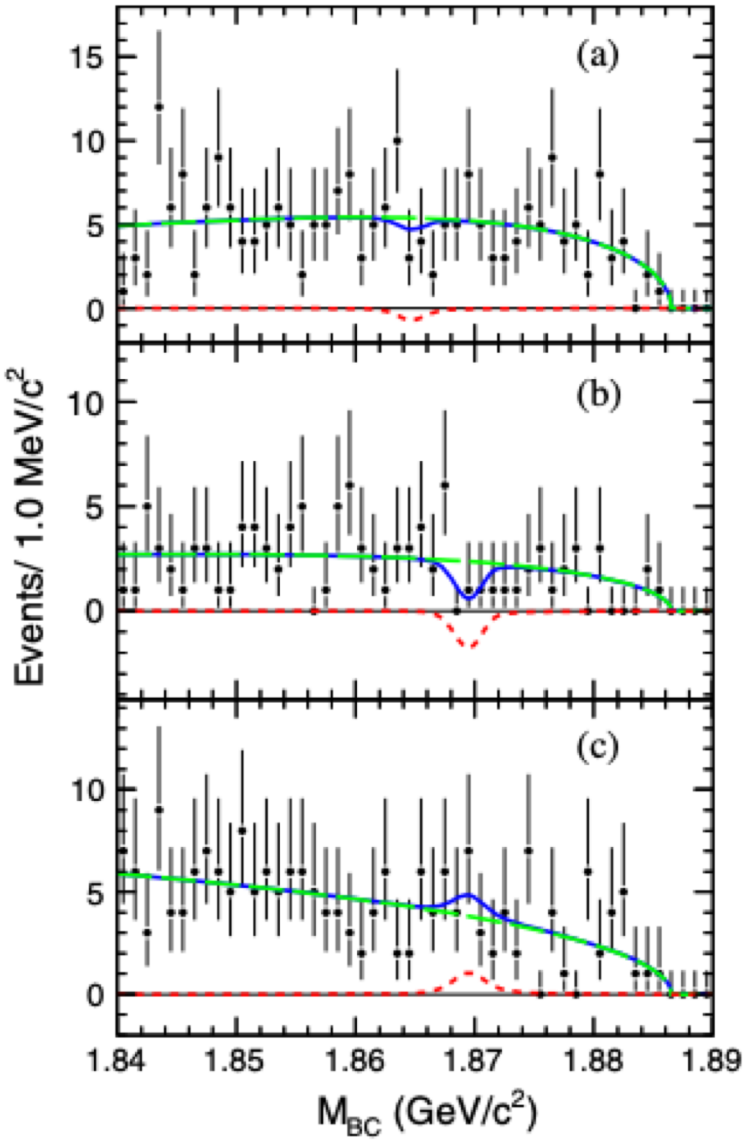


✓ ✓ ✗ ✓

- ✓ They searched (a) $D^0 \to K^-\pi^-e^+e^+$, (b)$D^+ \to K^0_S\pi^-e^+e^+$, and (d) $D^+ \to K^-\pi^0e^+e^+$
- ✓ $D^+ \to K^-\pi^0e^+e^+$ is suppressed due to the smaller CKM factor ($|\frac{V_{cd}V_{us}}{V_{cs}V_{ud}}|$~0.05)

03 LNV: $D \to K\pi e^+e^+$

Phys. Rev. D 99, (2019) 11, 112002



Fitting on the MBC spectra for the three LNV decays

Channel	ΔE (MeV)
$D^0 \to K^-\pi^-e^+e^+$	[−33.0, 19.7]
$D^+ \to K^0_S\pi^-e^+e^+$	[−30.6, 19.3]
$D^+ \to K^-\pi^0e^+e^+$	[−54.8, 24.4]

$$\mathcal{B}(D \to K\pi e^+e^+) = \frac{N_{sig}}{2\times N_D^{tot} \cdot \epsilon \cdot \mathcal{B}}$$

No obvious signal is observed

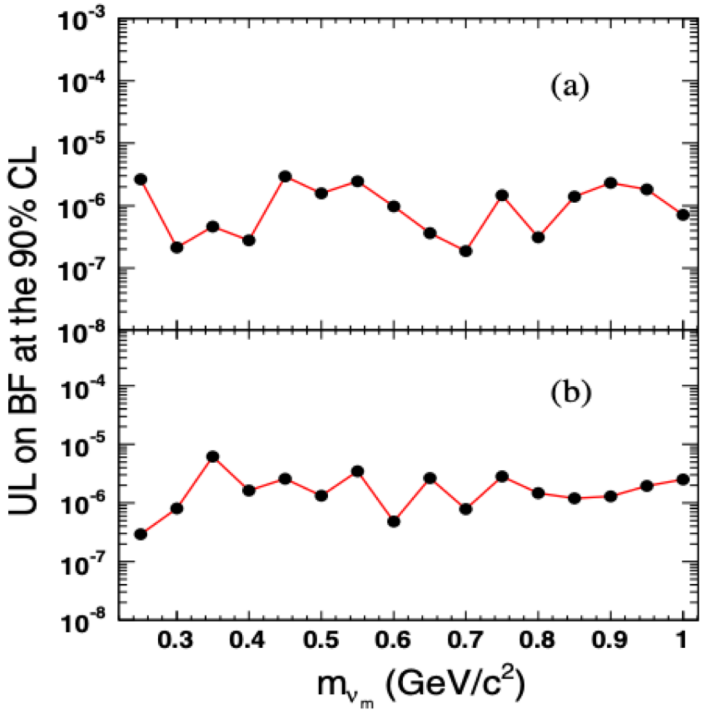
Channel	$\epsilon(\%)$	N_{sig}^{UL}	$\mathcal{B}_{sig}^{UL}(\times 10^{-6})$
$D^0 \to K^-\pi^-e^+e^+$	16.8	10.0	<2.8
$D^+ \to K^0_S\pi^-e^+e^+$	11.5	4.4	<3.3
$D^+ \to K^-\pi^0e^+e^+$	10.6	14.8	<8.5

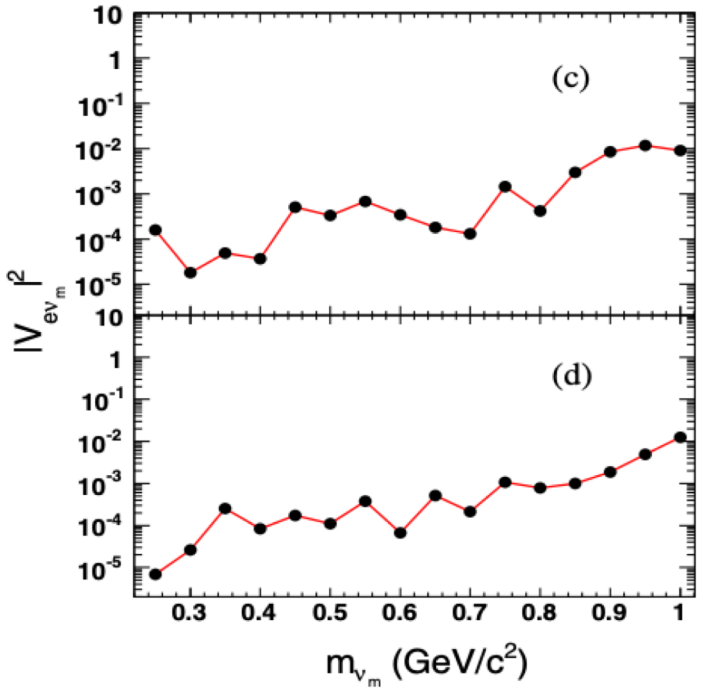
ULs of BF is ~ 10^{-6} at 90% C.L.

03 LNV: $D \to K\pi e^+e^+$

Phys. Rev. D 99, (2019) 11, 112002

- Searching for the Majorana (ν_m) in the decays of $D^0 \to K^- e^+ \nu_m, D^+ \to K_S^0 e^+ \nu_m$ with $\nu_m \to \pi e$; different mass assumptions ranging from 0.25 to 1.00 GeV/c^2 in LNV decays $D^0 \to K^-\pi^- e^+e^+, D^+ \to K_S^0\pi^- e^+e^+$
- Requirement of the invariant mass of any πe: $[m_\nu - 3\sigma, m_\nu + 3\sigma]$





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

CPC39,013101 (2015)

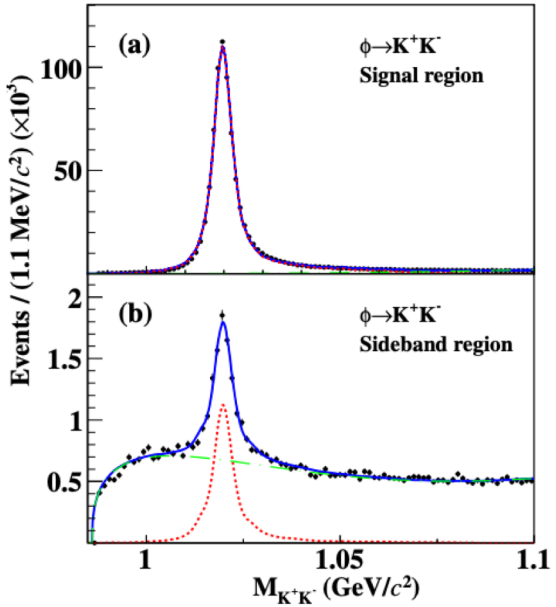
The ULs on the BFs at 90% CL: 10^{-7}~10^{-6}

The mixing matrix element $|V_{e\nu_m}|^2$ of a positron with the heavy Majorana neutrino in the charged current interaction.

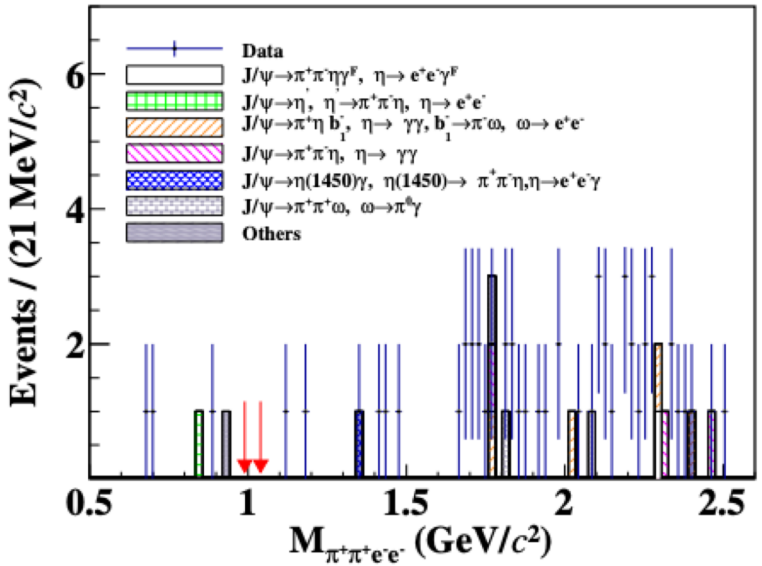
03 LNV: $\phi \to \pi^+\pi^+e^-e^-$ via $J/\psi \to \eta\phi$

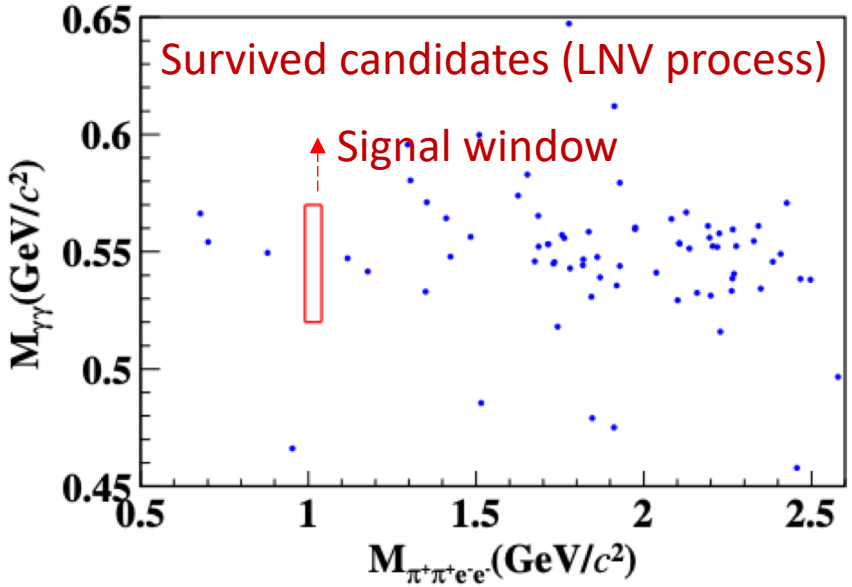
arXiv:2308.05490

- Data: $(1.0087 \pm 0.0044)\times10^{10}$ J/ψ events taken @3.097 GeV
- Although hadrons composed of the first generation quarks have been well explored in $0\nu2\beta$, constraints on the LNV process suggest that searching for LNV with non-first generation quark decays at collider experiments would be necessary



Fit to M_{KK} (reference mode)





Comparisons between data and MC (LNV process)

$$\mathcal{B}(\phi \to \pi^+\pi^+e^-e^-) = \mathcal{B}(\phi \to K^+K^-) \times \frac{N^{\rm net}_{\pi^+\pi^+e^-e^-}/\varepsilon_{\pi^+\pi^+e^-e^-}}{N^{\rm net}_{K^+K^-}/\varepsilon_{K^+K^-}},$$

No signal events are found

$\mathcal{B} < 1.3\times10^{-5}$ @90%C.L.

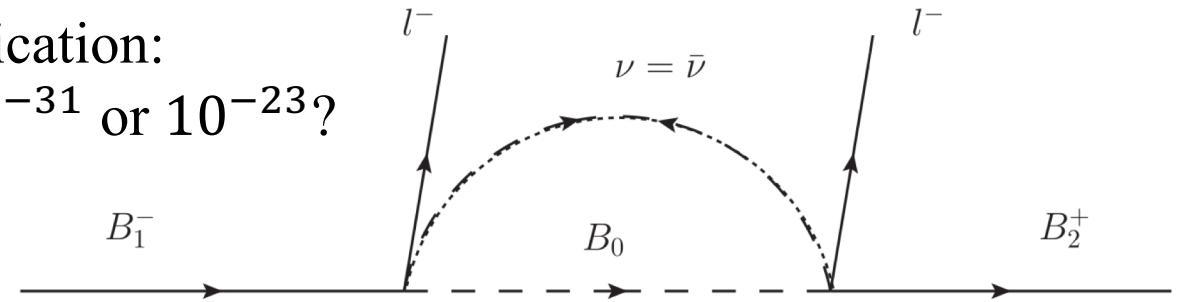
Submitted to CPC

03 LNV: $\Sigma^- \to pe^-e^-$ via $J/\psi \to \bar{\Sigma}(1385)^+\Sigma^-$

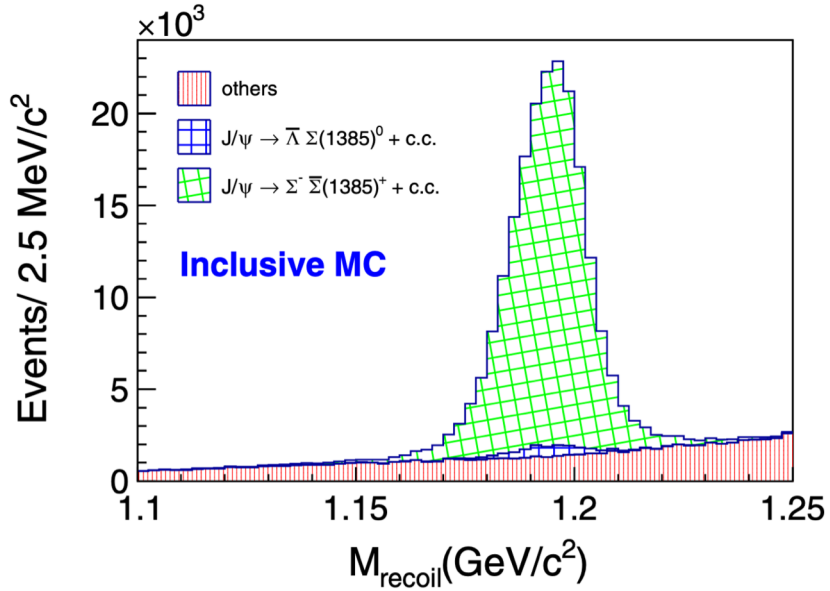
Phys. Rev. D 103, (2021), 052011

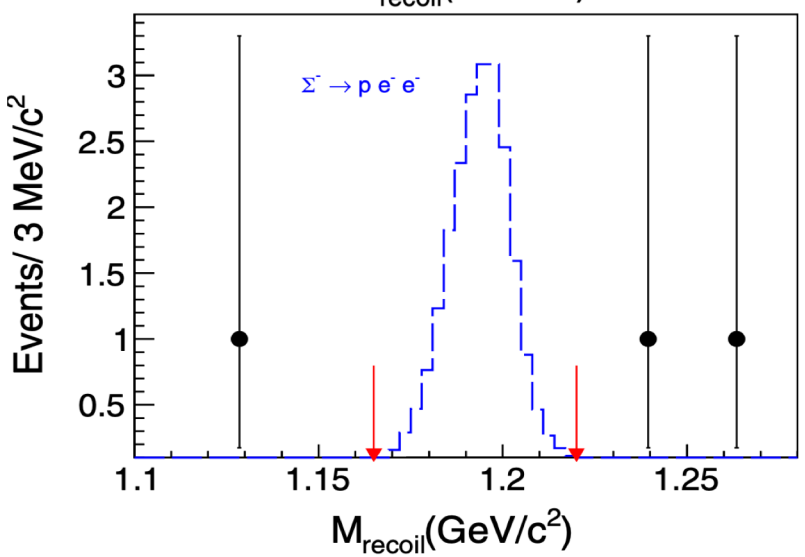
- Data: 1.3×10^9 J/ψ events taken @3.097 GeV
- Only a few experiments have reported searches in hyperon decays
- Two down-type (d or s) quarks convert into two up-quarks changing the charge of the hyperons according to the $\Delta Q = \Delta L = 2$ rule
- Reconstruction of $\bar{\Sigma}(1385)^+$: $\bar{\Sigma}(1385)^+ \to \bar{\Lambda}\pi^+$

Predication:
$\sim10^{-31}$ or 10^{-23}?



Dominant contributions:
a loop of a virtual baryon and a Majorana neutrino

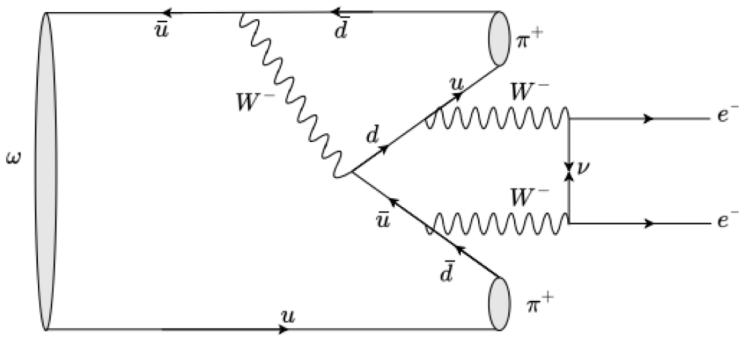


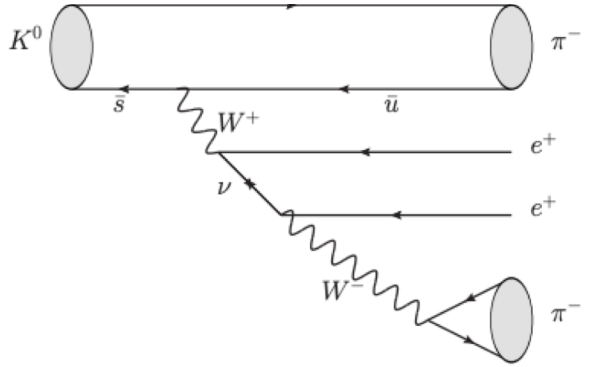


No signal events are found: $\mathcal{B} < 6.7\times10^{-5}$ @90%C.L.

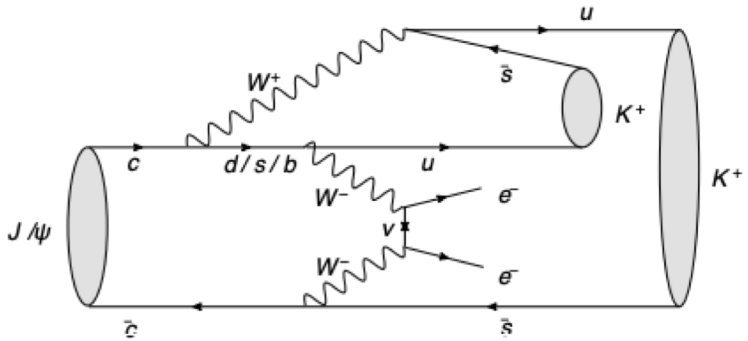
03 LNV: On going

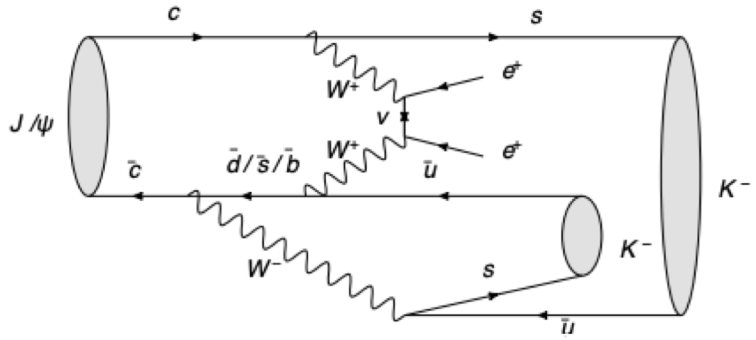
- BAM-00651: $K_S^0 \to \pi^+\pi^+e^-e^-$ via $J/\psi \to \bar{K}^{*0}K^0$ with ~1×10^{10} J/ψ events; Draft
- BAM-00770: $\eta \to \pi^+\pi^+e^-e^-$ via $J/\psi \to \eta\phi$ with ~1×10^{10} J/ψ events; Draft
- BAM-00747: $\omega \to \pi^+\pi^+e^-e^-$ via $J/\psi \to \eta\omega$ with ~1×10^{10} J/ψ events; Draft
- BAM-00666: $J/\psi \to \pi^+\pi^+e^-e^-$ with ~1×10^{10} J/ψ events; MEMO review





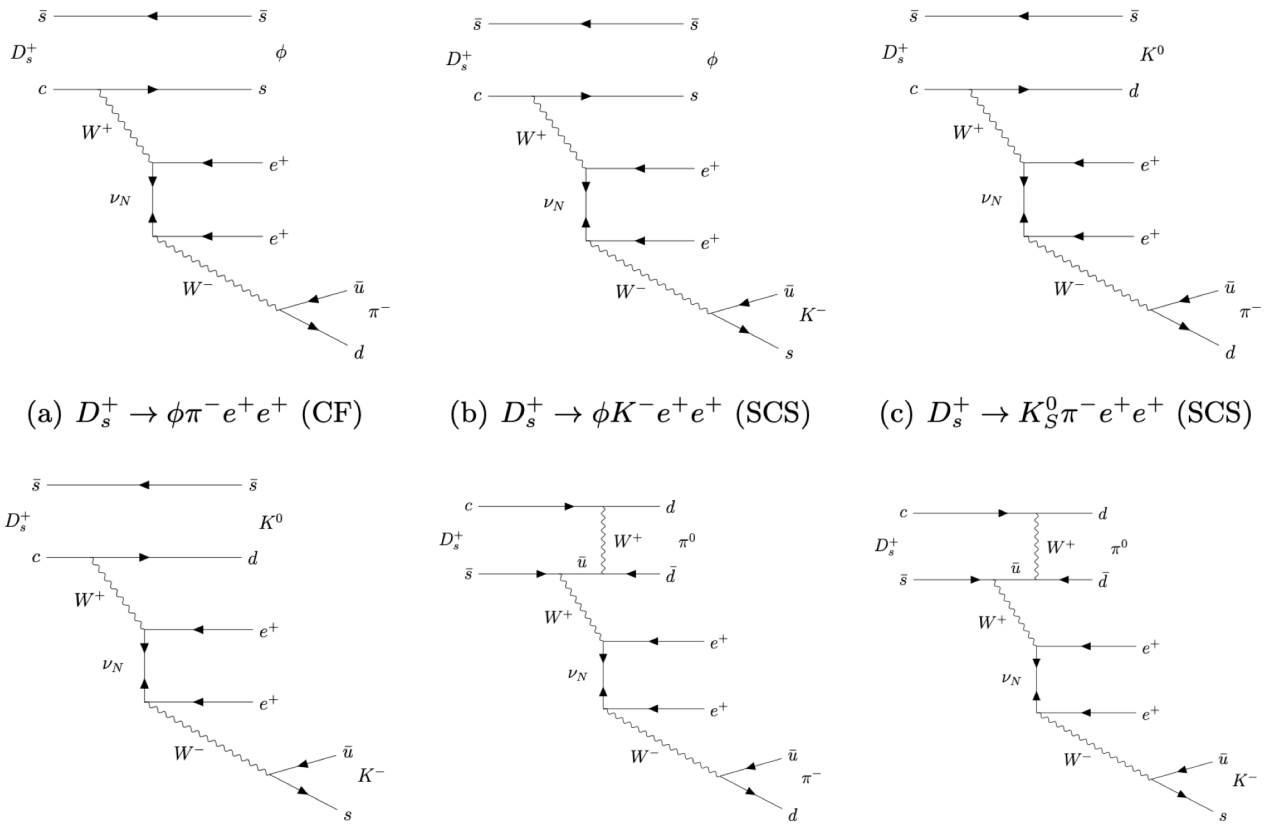
Possible Feynman diagrams





03 LNV: On going

- BAM-00786: $D_s^+ \to h^- h^0 e^+ e^+$ with 7.33 fb^{-1} data at 4.128-4.230 GeV; CWR finished



(a) $D_s^+ \to \phi\pi^- e^+ e^+$ (CF) (b) $D_s^+ \to \phi K^- e^+ e^+$ (SCS) (c) $D_s^+ \to K_S^0 \pi^- e^+ e^+$ (SCS)

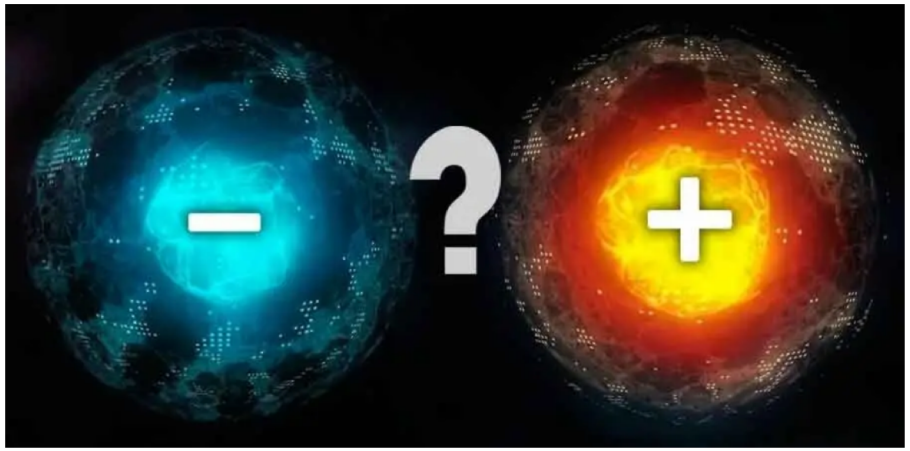
(d) $D_s^+ \to K_S^0 K^- e^+ e^+$ (DCS) (e) $D_s^+ \to \pi^- \pi^0 e^+ e^+$ (W-exc.) (f) $D_s^+ \to K^- \pi^0 e^+ e^+$ (W-exc.)

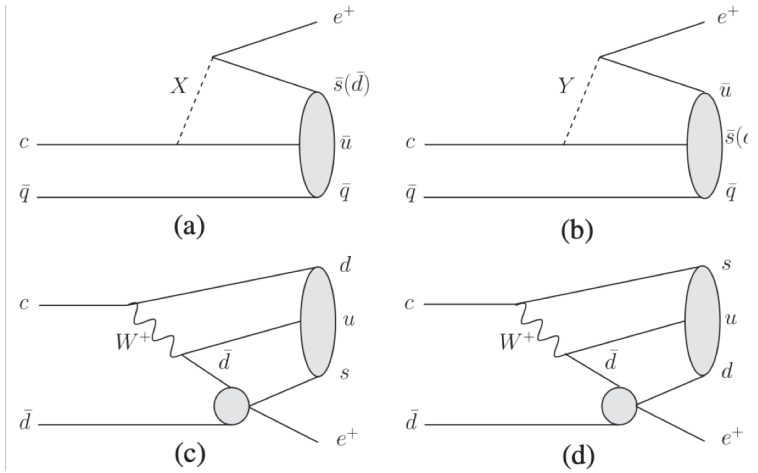
Possible Feynman diagrams

More new results are coming!

Another type of LNV process: BNV & LNV simultaniously break

- In the SM, baryon number (BN) is always conserved.
- However, baryon anti-baryon number is highly asymmetric in the universe. Baryon Number Violation? (BNV)
- BNV is allowed in GUT and SM extensions $\Delta(B-L)=0$
- Furthermore, another BNV under dimension seven operators allow $\Delta(B-L)=2$



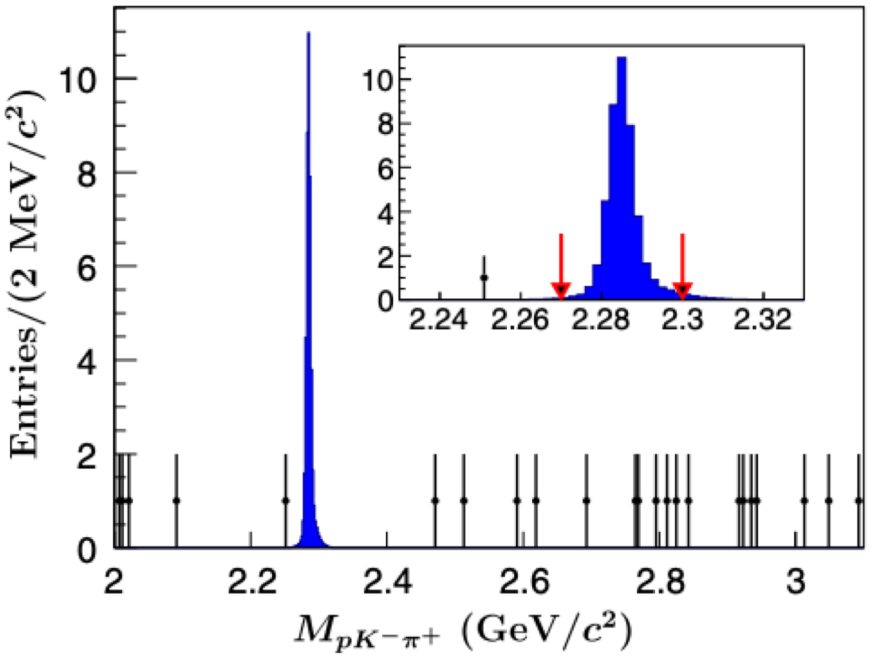


PRD 22 1694 (1980)
PRD 101 015017 (2020)
PRD 72 095001 (2005)
PRD 59 091303 (1999)
JHEP 05 030 (2009)
PRL 120 132501 (2018)
PRD 93 094026 (2016)
JHEP 08 068 (2011)

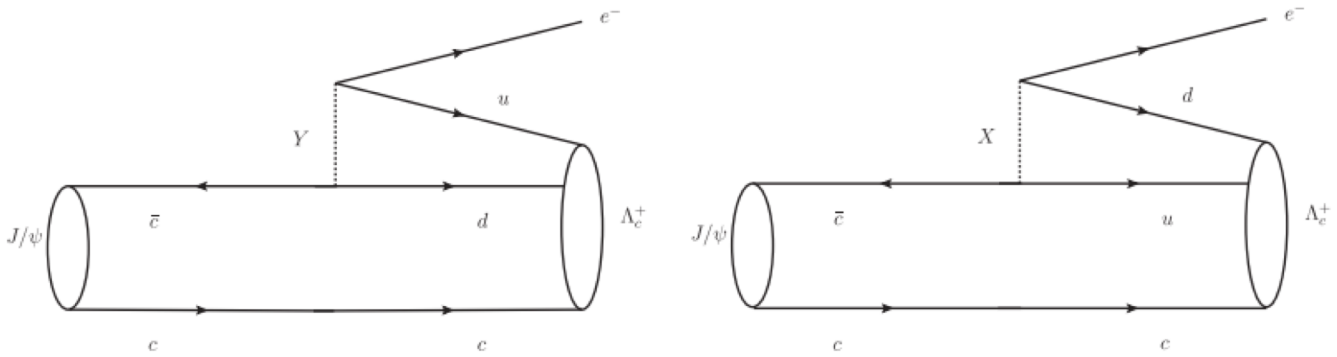
04 BNV&LNV: $J/\psi \to \Lambda_c^+ e^- + cc$

Phys. Rev. D 99, (2019) 7, 072006

- Data: 1.31×10^9 J/ψ events @3.097 GeV
- Searching for the processes in quarkonium decay opens a new avenue to study the BN violation
- $J/\psi \to \Lambda_c^+ e^-, \Lambda_c^+ \to pK^-\pi^+$
- The goodness of fit for the hypothesis of $pK^-\pi^+e^-$ is the best among $pK^-\pi^+e^-, \pi^+\pi^+\pi^-\pi^-, K^+K^+K^-K^-,$ $\pi^+\pi^-K^+K^-, \pi^+\pi^-p\bar{p}$ and $pK^-\pi^+e^-$



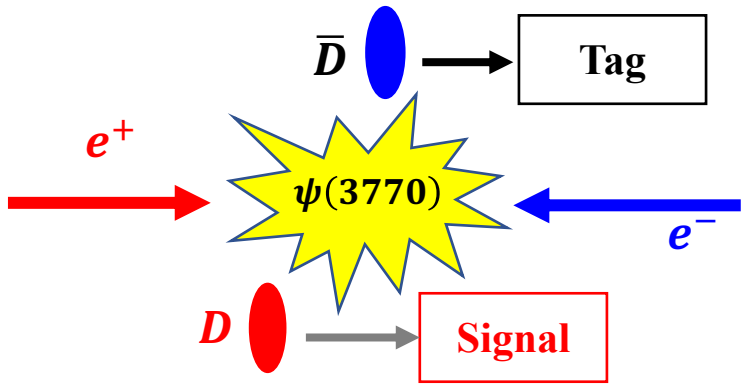
Distributions of $M_{pK^-\pi^+}$ for the $J/\psi \to \Lambda_c^+ e^-$ candidate events for signal MC simulation (shaded histogram) and data (dots with error bars)



$$\mathcal{B}(J/\psi \to \Lambda_c^+ e^-) < \frac{S_{90}}{N_{J/\psi}^{t0t} \times \mathcal{B}(\Lambda_c^+ \to pK^-\pi^+)} = 6.9\times10^{-8}$$

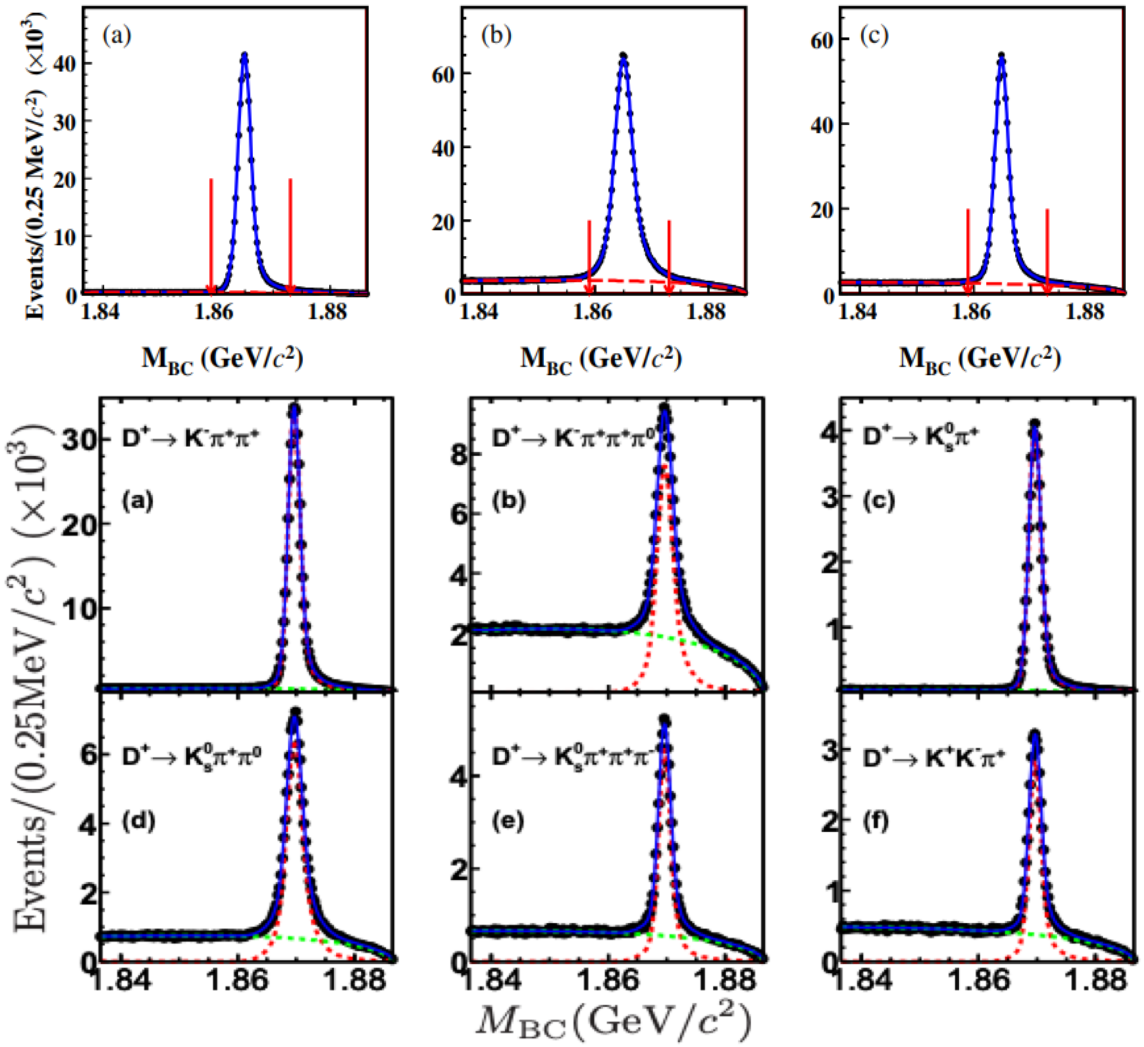
04 BNV&LNV in D decays

- Data: 2.93 fb^{-1} @ 3.773 GeV
- Double Tag analysis
- Absolute BFs
- Signal is clean and background is low
- Many sys. Uncertainties cancelled



$$E_{\rm beam} = \frac{\sqrt{s}}{2} = \frac{3.770}{2}\,{\rm GeV}, M_{\rm BC} = \sqrt{{E_{\rm beam}}^2 - {p_{\rm tot}}^2}$$

$$\Delta E = E_{\rm beam} - E_D$$



04 BNV&LNV: $D^0 \to pe^-$

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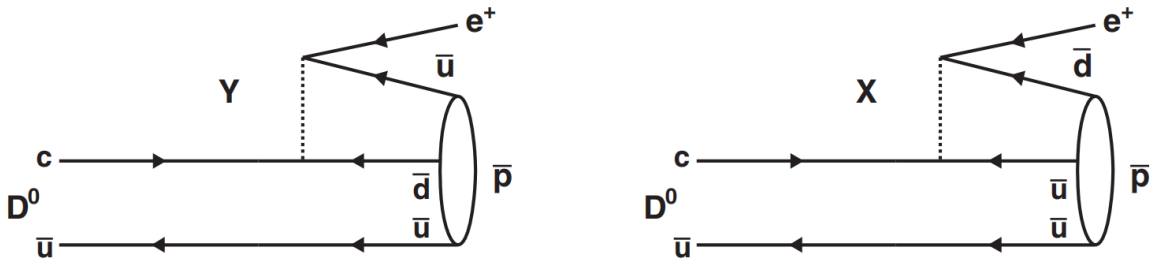
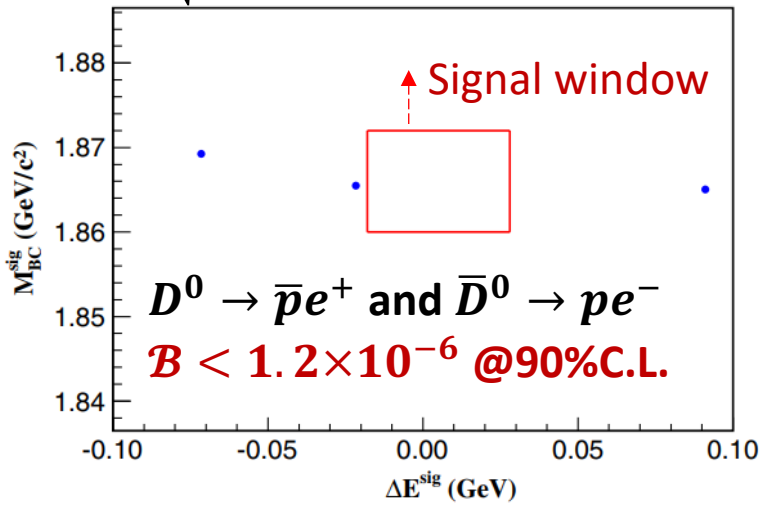
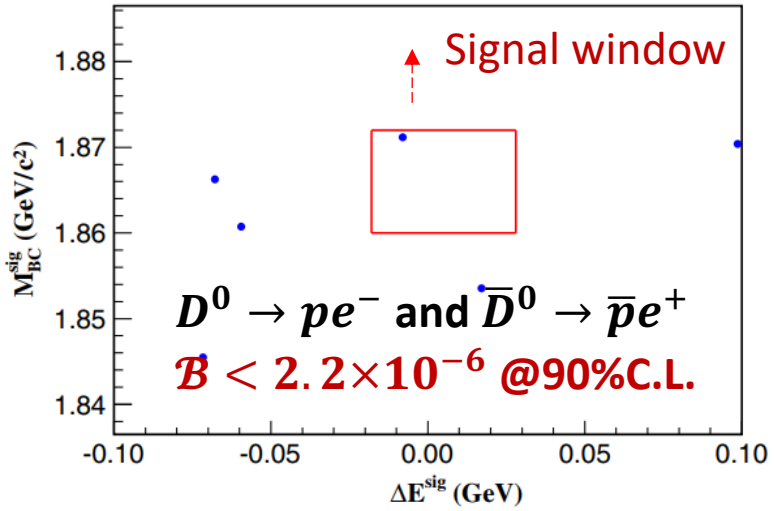
- Baryon anti-baryon number is highly asymmetric in the universe. Baryon Number Violation? (BNV)
- BNV is allowed in GUT and SM extensions $\Delta(B - L) = 0$
- BF: 10^{-39}
- Analyzing 2.93 $\mathbf{fb^{-1}}$ 3.773 GeV data
- Double Tag mothed is applied, very clean background



- $D^0 \to \bar{p}e^+$ in SU(5)
- X, Y : leptoquarks with electric charge $\frac{4}{3}e$ or $\frac{1}{3}e$

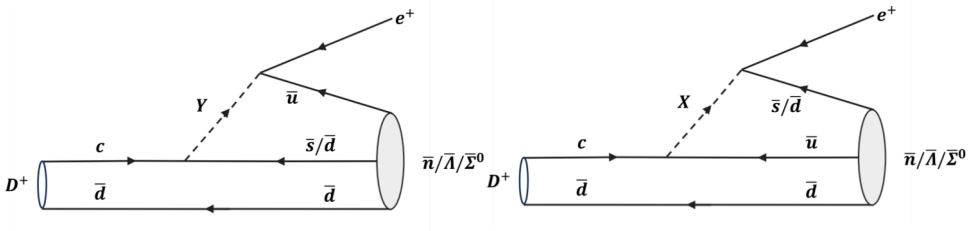
$$M_{BC}^{sig} = \sqrt{\frac{E_{beam}^2}{c^4} - \frac{|P_D|^2}{c^2}} \qquad \Delta E^{sig} = E_D - E_{beam}$$



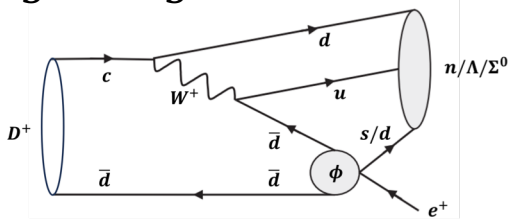


04 BNV&LNV: $D^+ \to (\mathbf{anti-})n/\Lambda/\Sigma^0 e^+$

- BNV in GUT and SM extensions $\Delta(\boldsymbol{B-L})=\mathbf{0}$
- BF: 10^{-29} for $D^+ \to \bar{\Lambda} e^+$
- BF: 10^{-39} for $D^+ \to \bar{n} e^+$
- Dimenson seven operators allow $\Delta(\boldsymbol{B-L})=\mathbf{2}$

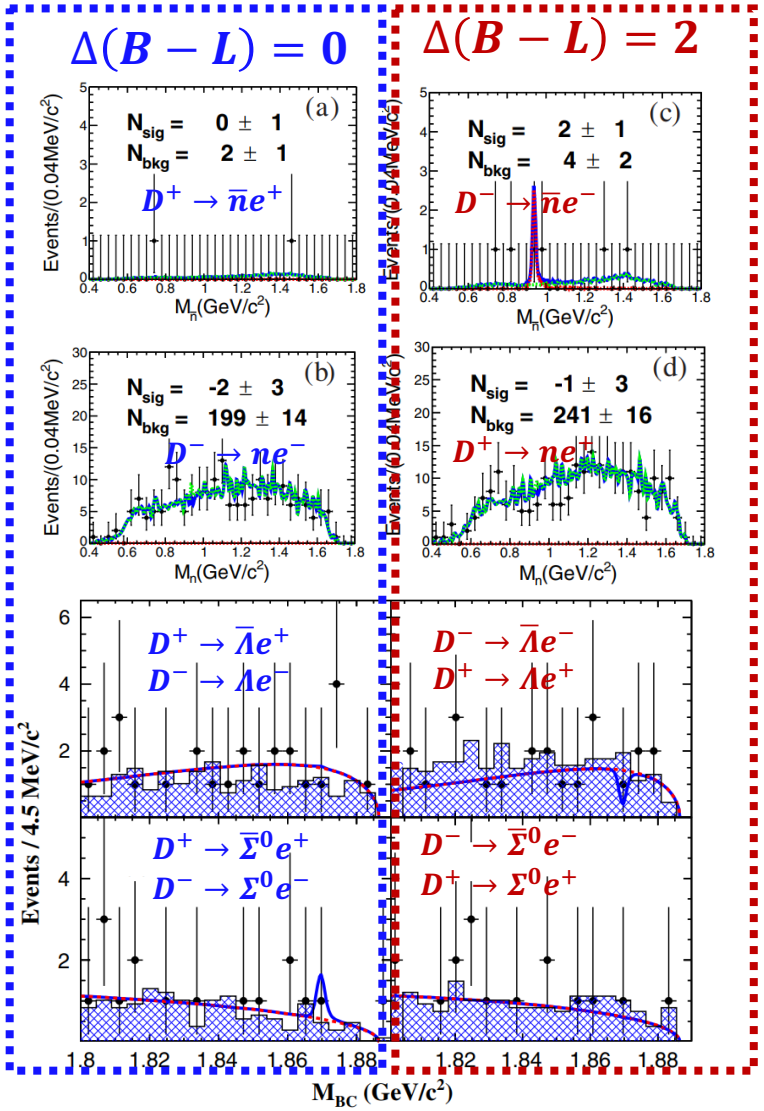


- X, Y : leptoquarks with electric charge $\frac{4}{3}e$ or $\frac{1}{3}e$
  - elementary scalar field ϕ



- n, $\bar{n}$ are regarded as missing particle
- Using $\Lambda \to p\pi^-$ to reconstruct Λ
- Using $\Sigma^0 \to \gamma\Lambda$ to reconstruct Σ^0

Mode (+c.c.)	$\mathcal{B}^{UL}$ @90%C.L.
$D^+ \to \bar{n}e^+$	$< 1.4\times10^{-5}$
$D^+ \to \bar{\Lambda}e^+$	$< 6.5\times10^{-7}$
$D^+ \to \bar{\Sigma}^0 e^+$	$< 1.3\times10^{-6}$
$D^+ \to ne^+$	$< 2.9\times10^{-5}$
$D^+ \to \Lambda e^+$	$< 1.1\times10^{-6}$
$D^+ \to \Sigma^0 e^+$	$< 1.7\times10^{-6}$



Phys. Rev. D 101, 031102(R) (2020)
Phys. Rev. D 106, 112009 (2022)

05 Summary

- The LNV processes are essential to probe New Physics beyond the Standard Model
- No obvious signals of NP processes have been found yet
- The ULs on the BFs in J/ψ decays at the 90% CL at level of 10^{-8}
- The ULs on the BFs in D decays at the 90% CL at level of $10^{-7}\sim10^{-5}$
- The ULs on the BFs at the 90% CL as a function of m_ν are at the level of $10^{-7}\sim10^{-6}$
- BESIII will collect 20 $\mathbf{fb^{-1}}$ @ 3.773 GeV data sample ($\boldsymbol{D\bar{D}}$)
- More & better results are coming soon!

Thanks for your attention!

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