Search for Baryon/Lepton number violation processes at BESIII

Xudong Yu
Peking University
(On behalf of BESIII collaboration)
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Outline

➔ Motivation

➔ BESIII experiment

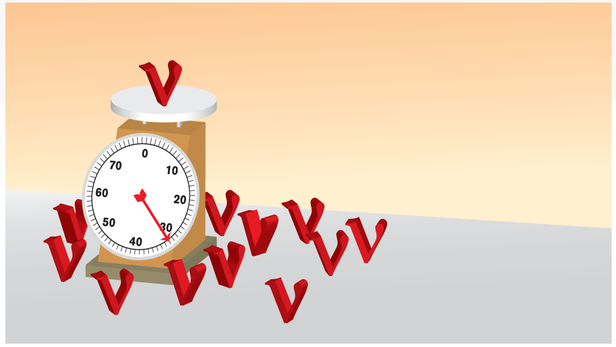
➔ Highlight results of BNL/LNV at BESIII

- BNV: $\Lambda - \bar{\Lambda}$ oscillation
- LNV: $D_s^+ \to h^+ h^0 e^+ e^+, \omega/\phi \to \pi^+\pi^+ e^- e^-$
- BNV & LNV: $\Xi^0 \to K^+ e^-/K^- e^+$

➔ Summary

Motivation

Neutrino mass vs LNV processes



- ➔ In SM, lepton number is a conserved quantity → Global $U(1)_L$ symmetry
  - ❖ Massless neutrinos: $U(1)_e \times U(1)_\mu \times U(1)_\tau$ is automatic global symmetry
- ➔ However, neutrino oscillations strongly convince that neutrinos have mass!
- ➔ Theoretically, “see-saw” mechanism can explain the neutrino mass
  - ❖ The small mass of observed light neutrino arises from heavy Majorana neutrino
  - ❖ If Neutrino is Dirac or Majorana particle is still an open question
- ➔ Majorana neutrino can be manifested through the LNV decays by $\Delta L = 2$
  - ❖ Most promissing way: neutrinoless double beta ($0\nu\beta\beta$) decay

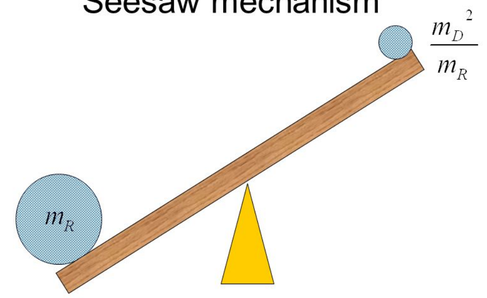
$$\mathcal{L} = -\frac{g}{\sqrt{2}} W_\mu^+ \sum_{l=e}^{\tau} V_{lN}^* \overline{N^c} \gamma^\mu P_L l + h.c.$$ CPC39,013101 (2015)

V_{lN}: Mixing matrix between the charged lepton l nuetrino ν_l and heavy Majorana neutrino

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

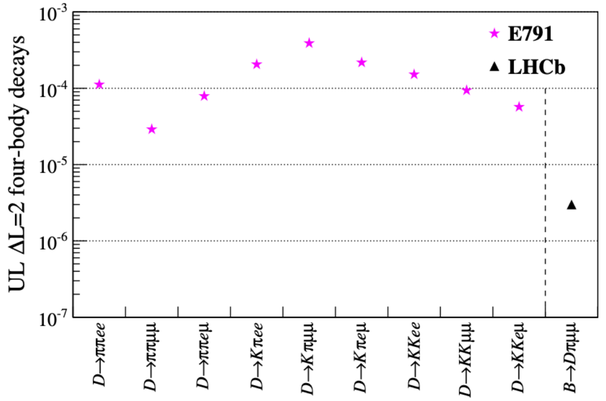
- ➔ Search for $\Delta L = 2$ process in hadron decays
  - ❖ Current experimental limit ⇒

Seesaw mechanism

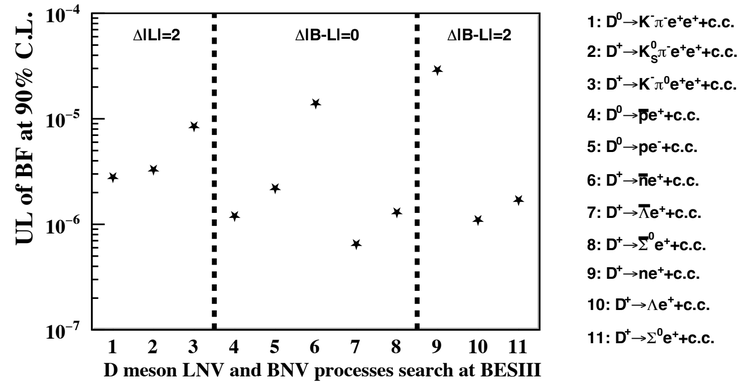


m_D	Dirac mass will be the same order as the others. (0.1~10 GeV)
m_R	Right handed Majorana mass will be at GUT scale 10^{15} GeV

Phys. Rev. D 98, (2018) 096004



arXiv:2403.11597

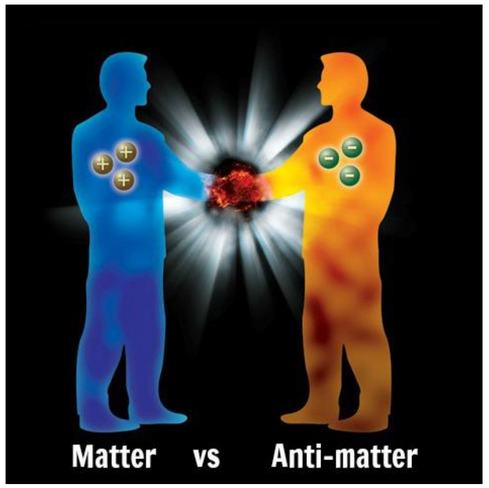


Matter-antimatter asymmetry vs BNV/LNV

➔ The matter-antimatter asymmetry observed in the Universe is one of the major frontier issues to be solved in physics

➔ To explain this asymmetry, Sakharov proposed three conditions:

- ❖ Violation of charge (C) and charge-parity (CP) symmetry
- ❖ **Violation of baryon number conservation**
- ❖ Deviation from thermal equilibrium



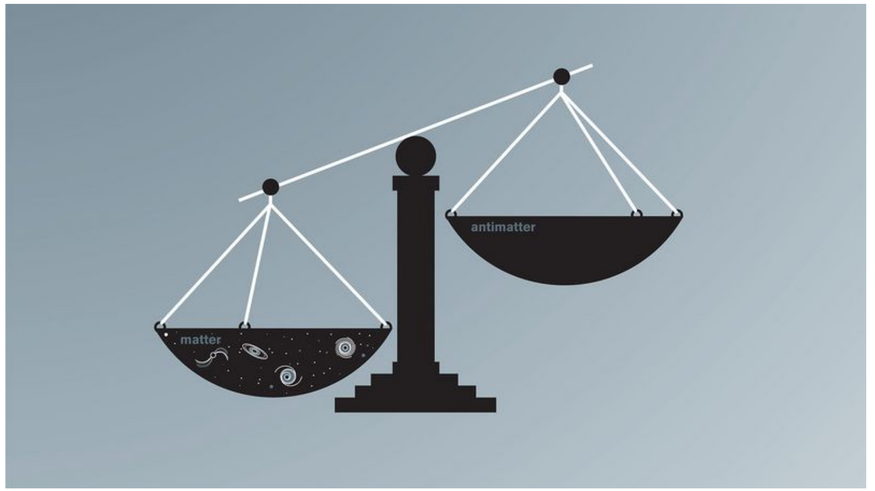
➔ BNV is allowed in grand unified theories (GUT) and SM extensions $\Delta(B-L)=0$

- ❖ Proton decay through leptoquarks: $p \to e^+\pi^0$
- ❖ BESIII has conducted many searches in $D, J/\psi, \Lambda$ decays

➔ Furthermore, another BNV under dimension seven operators allow $\Delta(B-L)=2$

- ❖ Neutron-antineutron oscillation
- ❖ Hyperon-antihyperon oscillation

Phys. Rev. D 101, 031102(R) (2020)
Phys. Rev. D 106, 112009 (2022)
Phys. Rev. D 105, 032006 (2022)
Phys. Rev. D 99, 072006 (2019)
Phys. Rev. D 105, L071101 (2022)



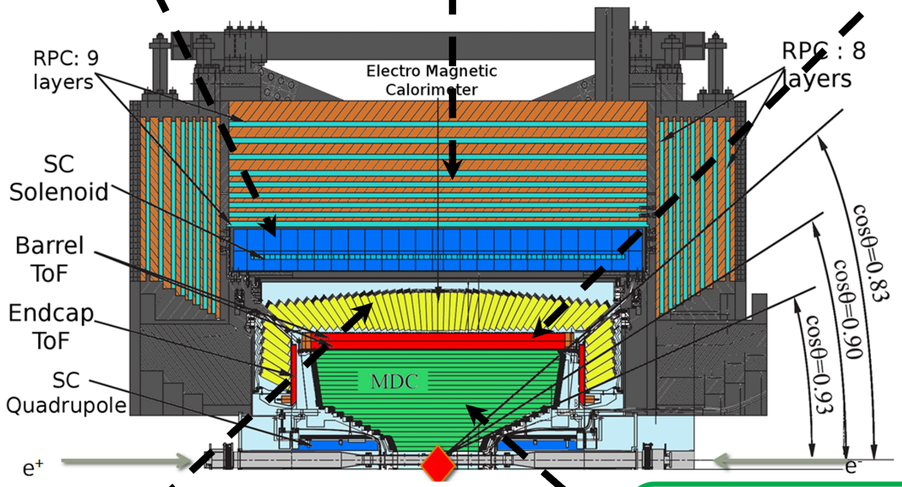
BESIII experiment

BEPCII & BESIII

Superconducting solenoid
- **1.0 T**

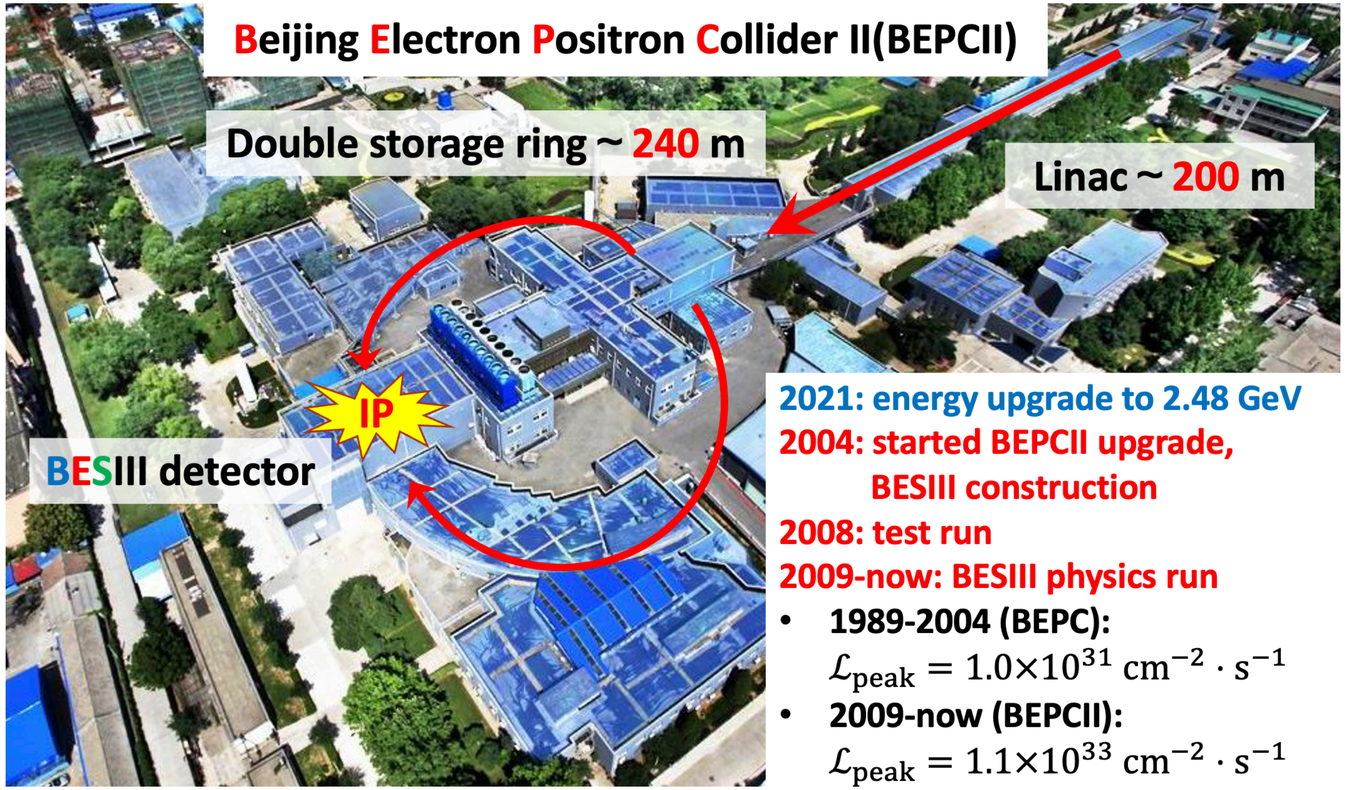
Muon Counter (MUC)
- 9 layers (barrel) + 8 layers (end-cap)

Time Of Flight (TOF)
- $\sigma_t = 90$ ps (barrel)
- $\sigma_t = 65$ ps (end cap)



Electromagnetic Calorimeter(EMC)
- $\Delta E/E = 2.5\%$ @ 1.0 GeV
- $\sigma_{\phi z} = 0.6$ cm @ 1.0 GeV

Main Drift Chamber (MDC)
- $\sigma_{xy} = 130$ μm
- $\Delta P/P = 0.5\%$ @ 1.0 GeV
- $\sigma_{dE/dx} = 6-7\%$

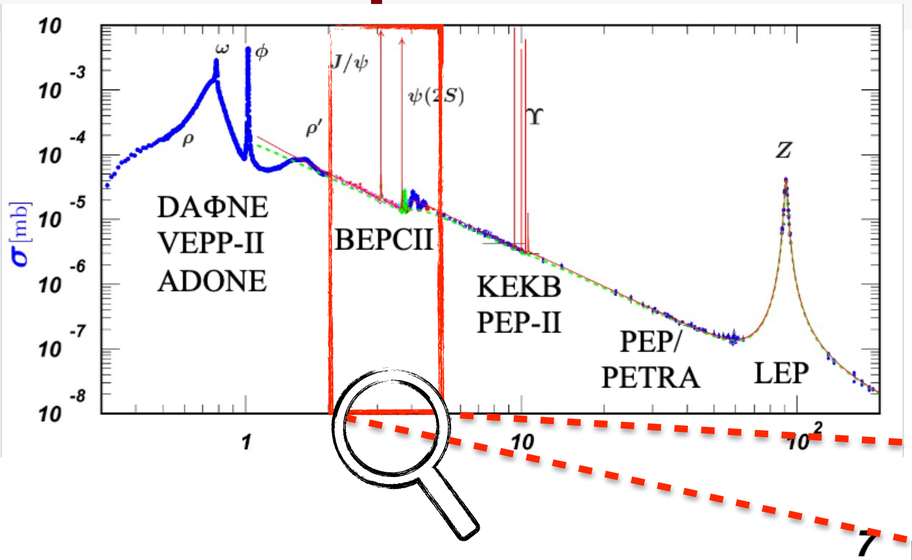


Beam energy: 1.0-2.475 GeV
Optimum energy: 1.89 GeV

2021: energy upgrade to 2.48 GeV
2004: started BEPCII upgrade, BESIII construction
2008: test run
2009-now: BESIII physics run

- **1989-2004 (BEPC):** $\mathcal{L}_{\text{peak}} = 1.0\times10^{31}\ \text{cm}^{-2}\cdot\text{s}^{-1}$
- **2009-now (BEPCII):** $\mathcal{L}_{\text{peak}} = 1.1\times10^{33}\ \text{cm}^{-2}\cdot\text{s}^{-1}$

Data samples at BESIII



- BESIII has collected the largest data samples of J/ψ and $\psi(3686)$ on the threshold in the world!
- $> 20\,\mathrm{fb}^{-1}$ data above 4.0 GeV in total

$\psi(3770)$ 20 fb^{-1} $\psi(4040)$ 0.5 fb^{-1} $\psi(4160)$ 3.2 fb^{-1} $\psi(4415)$ 1.1 fb^{-1}

J/ψ 1.0×10^{10}

$\psi(3686)$ 2.7×10^{9}

New physics searches at BESIII

- **c**harged **L**epton **F**lavor **V**iolation
- **L**epton/**B**aryon **N**umber **V**iolation
- C/CP violation
- …

THIS TALK

Symmetry violation

Exotic particle

Very rare decay

NEW PHYSICS

- Dark photon
- Axion-like particle
- Light Higgs
- SUSY particles
- …

- Charmonium weak decay
- **F**lavor **C**hanging **N**eutral **C**urrent
- …

Other process

Strategies

- Invisible decay
- **L**epton **U**niversality **V**iolation
- …

- Common statistic and standards
- Sharing methods, tool and codes
- Uniform semi-blind strategy and datasets

- Nation Science Review 8, nwab189 (2021), arXiv: 2102.13290
- New Physics Program of BES, D.Y. Wang, in “30 Years of BES Physics”

Baryon number violation

BNV: $\Lambda - \bar{\Lambda}$ oscillations

➔ Baryon number symmetry broken: one of three conditions for generating matter-antimatter asymmetry

➔ Crucial test of BNV is neutron-antineutron ($N - \bar{N}$) oscillation in theory and experiment

- ❖ If $N - \bar{N}$ exists, then $\Lambda - \bar{\Lambda}$ oscillation may also take place

Phys. Rev. D 81, 051901(R) (2010)

➔ Theorists proposed to study $\Lambda - \bar{\Lambda}$ oscillation at BESIII using $\Lambda/\bar{\Lambda}$ produced by J/ψ decays

Time evolution of $\Lambda - \bar{\Lambda}$ oscillations is described by a Schrödinger-like equation

$$i\frac{\partial}{\partial t}\begin{pmatrix}\Lambda(t)\\ \bar{\Lambda}(t)\end{pmatrix} = M\begin{pmatrix}\Lambda(t)\\ \bar{\Lambda}(t)\end{pmatrix}$$

$$M = \begin{pmatrix} m_\Lambda - \Delta E_\Lambda & \delta m_{\Lambda\bar{\Lambda}} \\ \delta m_{\Lambda\bar{\Lambda}} & m_{\bar{\Lambda}} - \Delta E_{\bar{\Lambda}} \end{pmatrix}$$

$\delta m_{\Lambda\bar{\Lambda}}$ is the mass splitting generated by $\Delta B = 2$ transitions between Λ and $\bar{\Lambda}$
ΔE is the energy split due to an external magnetic field: $\Delta E_{\Lambda/\bar{\Lambda}} = -\vec{\mu}_{\Lambda/\bar{\Lambda}} \cdot \vec{B}$
The magnetic field splitting effect is negligible at BESIII scenario

The oscillation rate of generating a $\bar{\Lambda}$ with a beam of free Λ after time t
t is the time when the oscillation is observed (decay)

$$P(\bar{\Lambda}, t) = \sin^2(\delta m_{\Lambda\bar{\Lambda}} \cdot t) e^{-t/\tau_\Lambda}$$

The time-integrated oscillation probability of $\Lambda \to \bar{\Lambda}$

$$P(\bar{\Lambda}) = \frac{\int_0^\infty \sin^2(\delta m_{\Lambda\bar{\Lambda}} \cdot t) e^{-t/\tau_\Lambda} dt}{\int_0^\infty e^{-t/\tau_\Lambda} dt}$$

The oscillation parameter can be deduced as

$$\delta m_{\Lambda\bar{\Lambda}} = \sqrt{\frac{P(\Lambda)}{2\tau_\Lambda^2}}$$

$\Lambda - \bar{\Lambda}$ oscillations in $J/\psi \to pK^-\bar{\Lambda}$

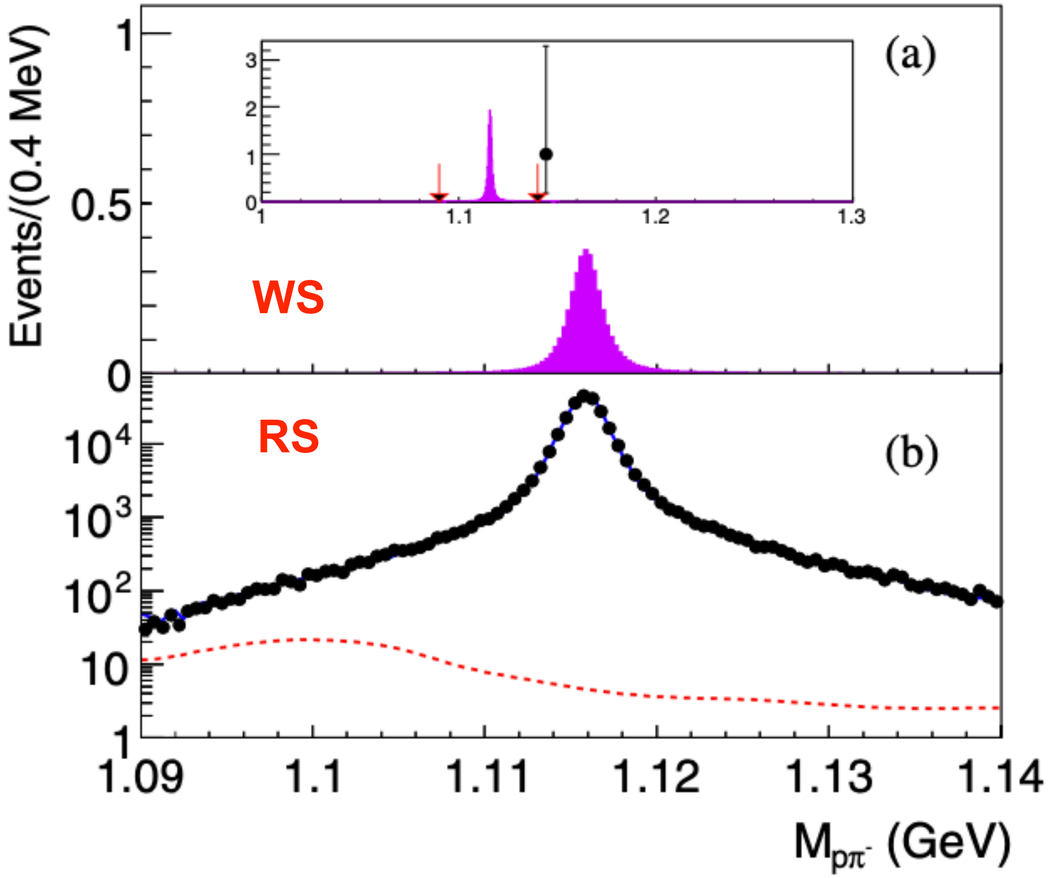
Phys. Rev. Lett. 131, 121801 (2023)

- First search for $\Lambda - \bar{\Lambda}$ oscillations based on the decay $J/\psi \to pK^-\bar{\Lambda}$
- Data: 1.31×10^9 J/ψ events taken @ 3.097 GeV (1/10 of full data set)
- RS: $J/\psi \to pK^-\bar{\Lambda}(\bar{\Lambda} \to \bar{p}\pi^+)$, WS: $J/\psi \to pK^-\Lambda(\Lambda \to p\pi^-)$

- No signal event for the WS decay is observed
- With the assumption of no CP violation in Λ decay in the process $J/\psi \to pK^-\bar{\Lambda}$, the UL of $\Lambda - \bar{\Lambda}$ oscillation rate at 90% CL is determined to be

$$\mathscr{P}(\Lambda) < \frac{S_{\rm WS}^{90\%}}{N_{\rm RS}^{\rm obs}/\epsilon_{\rm RS}} = 4.4 \times 10^{-6}$$

- UL of oscillation parameter $\delta m_{\Lambda\bar{\Lambda}} < 3.8 \times 10^{-18}\,\text{GeV}$ at 90% CL
  - Corresponding to an oscillation time ($\tau_{\rm osc} = 1/\delta m_{\Lambda\bar{\Lambda}}$) limit of $\tau_{\rm osc} > 1.7 \times 10^{-7}\,\text{s}$ at 90% CL



$\Lambda - \bar{\Lambda}$ oscillations in $J/\psi \to \Lambda\bar{\Lambda}$

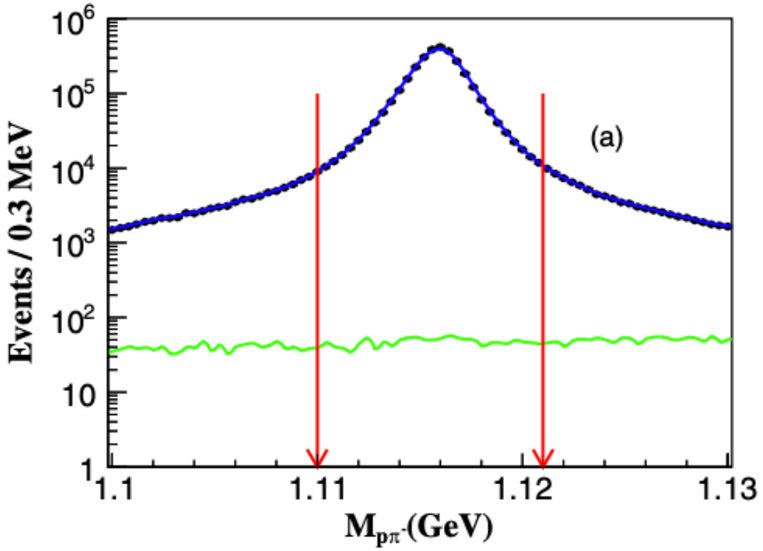
Phys. Rev. D 111, 052014 (2025)

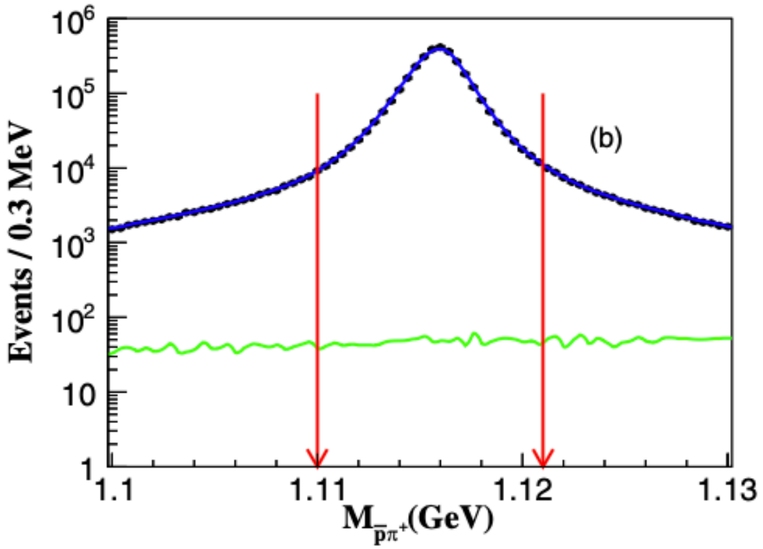
- Data: $(1.0087 \pm 0.0044) \times 10^{10}$ J/ψ events taken @ 3.097 GeV
- RS: $J/\psi \to \Lambda\bar{\Lambda}$, WS: $J/\psi \to \Lambda\Lambda + \mathrm{c.c.}$

- No signal or background events are found
- UL of $\Lambda - \bar{\Lambda}$ oscillation rate at 90% CL is determined to be

$$\mathscr{P}(\Lambda) = \frac{\mathscr{B}(J/\psi \to \Lambda\Lambda + \mathrm{c.c.})}{\mathscr{B}(J/\psi \to \Lambda\bar{\Lambda})} < \frac{N_{\mathrm{WS}}^{\mathrm{UL}}}{N_{\mathrm{RS}}^{\mathrm{obs}}/\epsilon_{\mathrm{RS}}} = 1.4 \times 10^{-6}$$

- UL of oscillation parameter $\delta m_{\Lambda\bar{\Lambda}} < 2.1 \times 10^{-18}\,\mathrm{GeV}$
  - Corresponding to an oscillation time ($\tau_{\mathrm{osc}} = 1/\delta m_{\Lambda\bar{\Lambda}}$) limit of $\tau_{\mathrm{osc}} > 3.1 \times 10^{-7}\,\mathrm{s}$ at 90% CL
- More stringent constraints on ULs than last measurement





Lepton number violation

LNV decays: $D_s^+ \to h^- h^0 e^+ e^+$

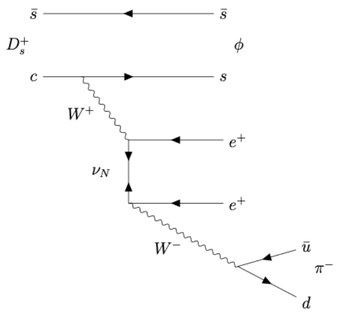
JHEP 01 (2025) 109

- ➔ $h^- : K^-/\pi^-, h^0 : \pi^0/K_S^0/\phi \Rightarrow$ 6 signal channels in total
  - ❖ CF: $D_s^+ \to \phi\pi^- e^+ e^+$; SCS: $D_s^+ \to \phi K^- e^+ e^+$, $D_s^+ \to K_S^0 \pi^- e^+ e^+$; DCS: $D_s^+ \to K_S^0 K^- e^+ e^+$, $D_s^+ \to \pi^-\pi^0 e^+ e^+$, $D_s^+ \to K^-\pi^0 e^+ e^+$;
- ➔ Data: 7.33 fb^{-1} data taken between 4.128 to 4.226 GeV
- ➔ $e^+e^- \to D_s^{*\pm} D_s^{\mp}$, single tag method

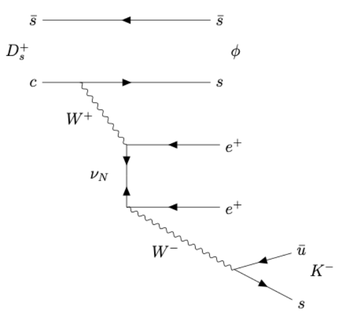
$$\mathcal{B}(D_s^+ \to h^- h^0 e^+ e^+) = \frac{N_{\rm sig}}{2 \cdot N_{D_s^{*\pm} D_s^{\mp}} \cdot \epsilon \cdot \mathcal{B}_{\rm inter}}$$

- ➔ First measurement of four-body $\Delta L = 2$ D_s^+ decay
- ➔ Some model predictions up to $\mathcal{O}(10^{-6})$

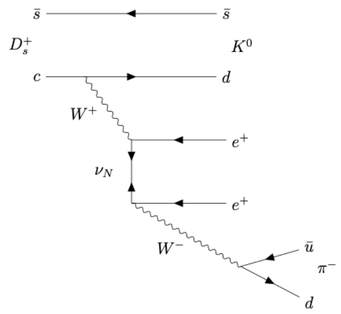
JHEP 05 (2009) 030
JHEP 08 (2013) 066
Chin. Phys. C 39 (2015) 013101
Phys. Rev. D 98 (2018) 096004



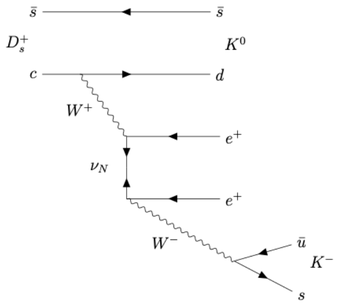
(a) $D_s^+ \to \phi\pi^- e^+ e^+$ (CF).



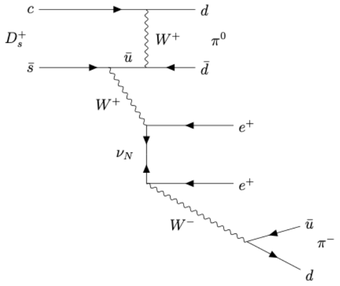
(b) $D_s^+ \to \phi K^- e^+ e^+$ (SCS).



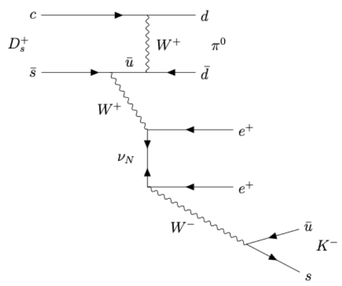
(c) $D_s^+ \to K_S^0 \pi^- e^+ e^+$ (SCS).



(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.).

Feynman diagrams

ULs of BFs of $D_s^+ \to h^- h^0 e^+ e^+$

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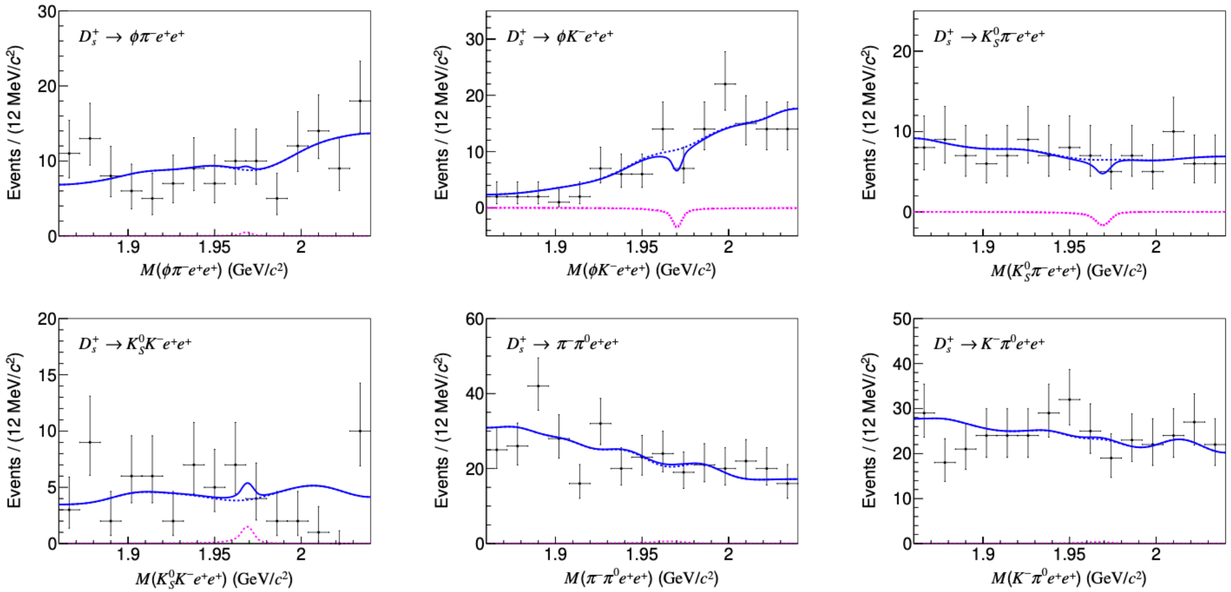
➔ No obvious signal is observed

➔ Upper limits of BFs of $D_s^+ \to h^- h^0 e^+ e^+$ decays at the 90% C.L.



Fit to invariant mass spectrum

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	$3.4\ (3.9) \times 10^{-5}$

ULs of BFs at 90% at 10^{-5}

Search for Majorana neutrino in $D_s^+ \to \phi\pi^- e^+ e^+$

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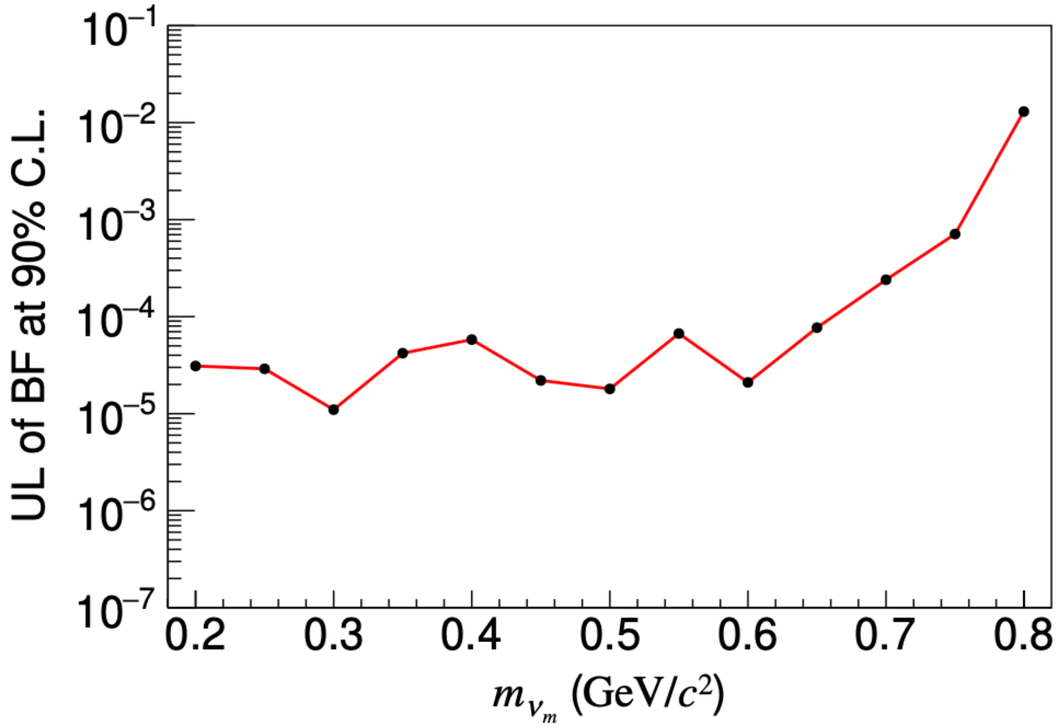
➔ Searching for Majorana (ν_m) in the decay of $D_s^+ \to \phi e^+ \nu_m (\to \pi^- e^+)$

- Different assumptions of m_{ν_m} ranging from 0.20 to 0.80 GeV

➔ Require the invariant mass of any $\pi^- e^+$ combination (two combinations per event) to be within the range of $[m_{\nu_m} - 5\sigma, m_{\nu_m} + 4\sigma]$

- σ is the resolution of mass distribution from MC simulation

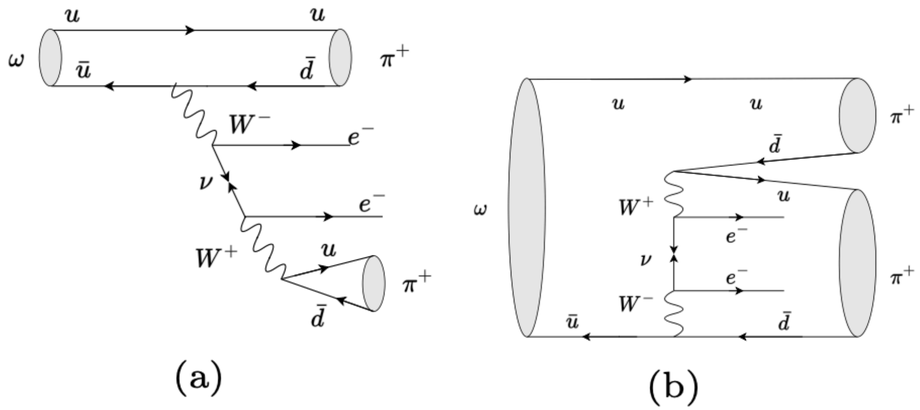


ULs of BFs at 90% CL as a function of m_{ν_m} range from around $10^{-5} - 10^{-2}$

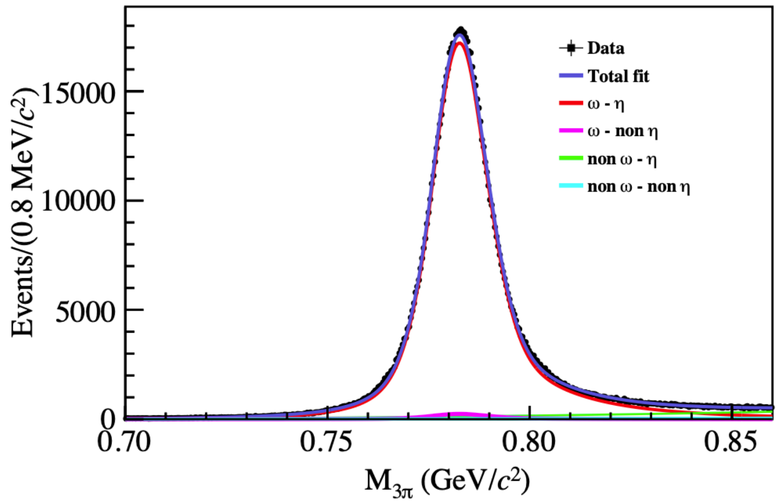
LNV decay: $\omega \to \pi^+\pi^+e^-e^-$ via $J/\psi \to \eta\omega$

arXiv:2504.21539
Accepted by Chin. Phys. C

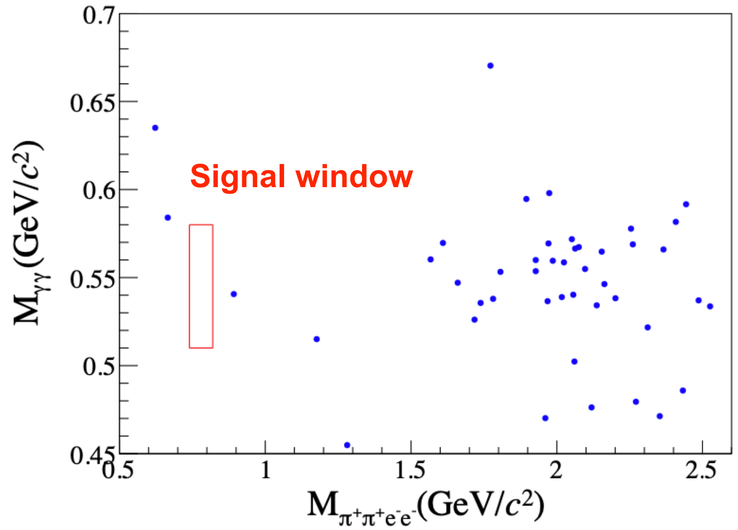
- Data: $(1.0087 \pm 0.0044) \times 10^{10}$ J/ψ events taken @ 3.097 GeV
- Relative measurement to the reference channel: $\omega \to \pi^+\pi^-\pi^0$ via $J/\psi \to \omega\eta$



Possible Feynman diagrams



Fit to $M_{3\pi}$ (reference mode)



$M_{\pi^+\pi^+e^-e^-}$ vs $M_{\gamma\gamma}$ 2D distribution in data

$$\mathcal{B}(\omega \to \pi^+\pi^+e^-e^-) = \mathcal{B}(\omega \to \pi^+\pi^-\pi^0)$$

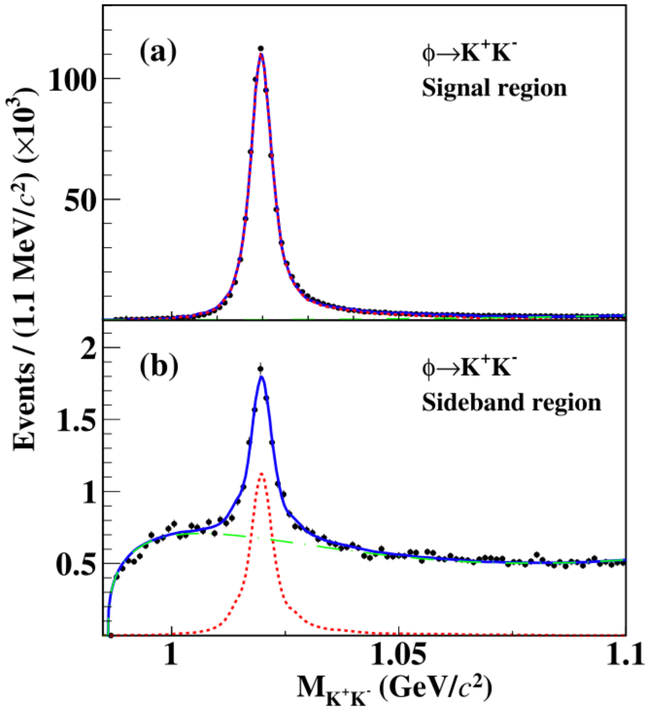
$$\times\mathcal{B}(\pi^0 \to \gamma\gamma) \times \frac{N^{\rm sig}_{\pi^+\pi^+e^-e^-}/\epsilon_{\pi^+\pi^+e^-e^-}}{N^{\rm ref}_{\pi^+\pi^-\pi^0}/\epsilon_{\pi^+\pi^-\pi^0}}$$

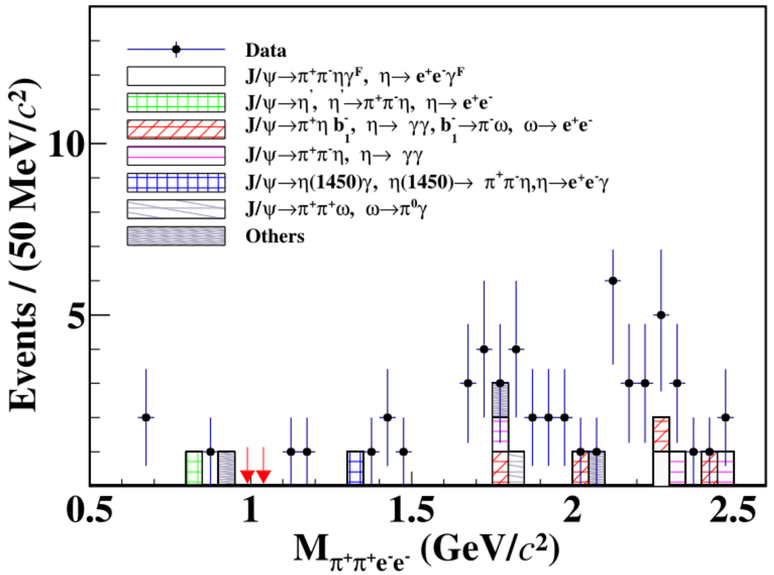
No signal events are found, UL on BF of $\omega \to \pi^+\pi^+e^-e^-$ to be 2.6×10^{-6} at the 90% CL

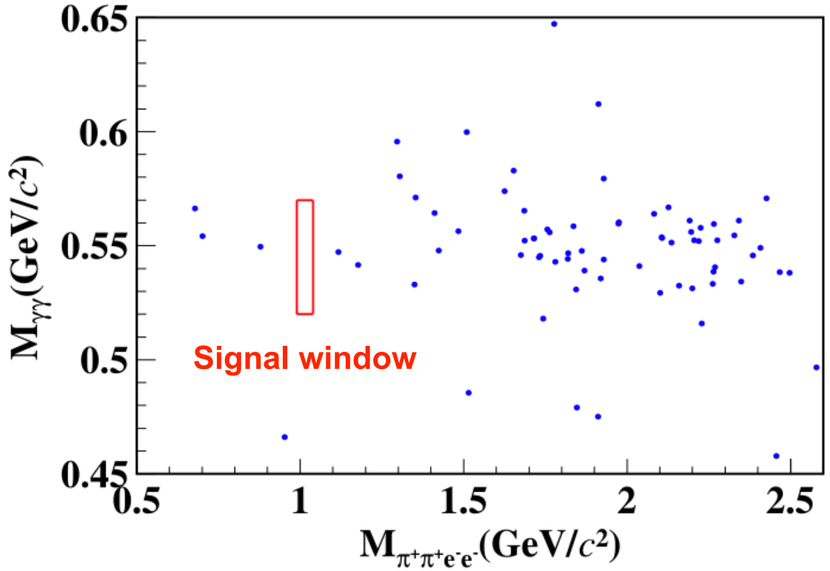
LNV decay: $\phi \to \pi^+\pi^+e^-e^-$ via $J/\psi \to \eta\phi$

Chin. Phys. C 49, 043001 (2025)

- Hadron composed of the first generation quarks have been well explored in $0\nu2\beta$, searching for LNV with non-first generation quark decay provides more constraints on LNV process
- Data: $(1.0087 \pm 0.0044) \times 10^{10}$ J/ψ events taken @ 3.097 GeV
- Relative measurement to the reference channel: $\phi \to K^+K^-$ via $J/\psi \to \phi\eta$







Comparisons between data and MC (LNV process)

Fit to $M_{K^+K^-}$ (reference mode)

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

No signal events are found, UL on BF of $\phi \to \pi^+\pi^+e^-e^-$ to be 1.3×10^{-5} at the 90% CL

Baryon & Lepton number violation

BNV&LNV decays: $\Xi^0 \to K^{\mp}e^{\pm}$

Phys. Rev. D **108**, 012006 (2023)

➔ Simultaneous BNV & LNV break

- ❖ BNV is allowed in GUT and SM extensions $\Delta(B-L)=0$
  - ▸ SU(5) GUT proposes the existence of two new gauge bosons, X with electric charge $4/3e$ and Y with electric charge $1/3e$
- ❖ Another class of SM extensions with NLO BNV effects uses dimension-seven operators allows $\Delta(B-L)=2$
  - ▸ SM embedded in GUTs such as SO(10), which mediated by an elementary scalar field ϕ

Phys. Rev. Lett. 32, 438 (1974)
Phys. Lett. B 231, 65 (1989)
Phys. Rev. D 22, 1694 (1980)
Nucl. Phys. B173, 269 (1980)
Phys. Rev. Lett. 109, 091803 (2012)

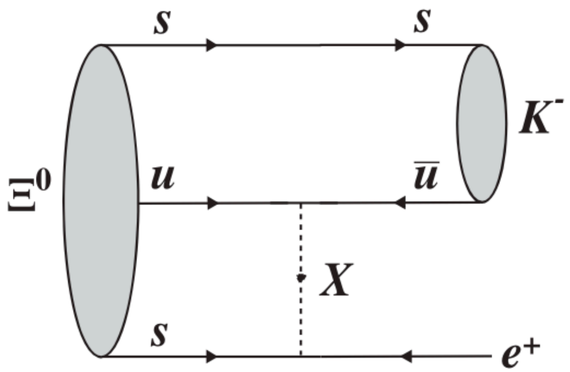
➔ Strictest constraint on protion BNV decay: $\tau/\mathcal{B}(p \to \mu^+\pi^0) > 1.6\times10^{34}$ years at 90% CL

- ❖ Proton stability stringently constrains BNV decays involving higher generations quarks

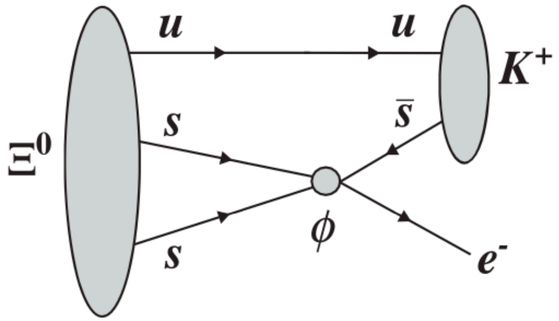
➔ CLAS experiment search for Λ BNV decays, ULs on BFs in the range of $10^{-5} \sim 10^{-7}$ at 90% CL

➔ Search for $\Xi^0 \to K^{\mp}e^{\pm}$ with lepton number violation as a consequence of BNV

Phys. Rev. D 102, 112011 (2020)
Phys. Rev. D 72, 095001 (2005)
Phys. Rev. D 92, 072002 (2015)



$\Xi^0 \to K^-e^+$ with $\Delta(B-L)=0$ mediated by a gauge boson X



$\Xi^0 \to K^+e^-$ with $\Delta(B-L)=2$ mediated by a elementary scalar field ϕ

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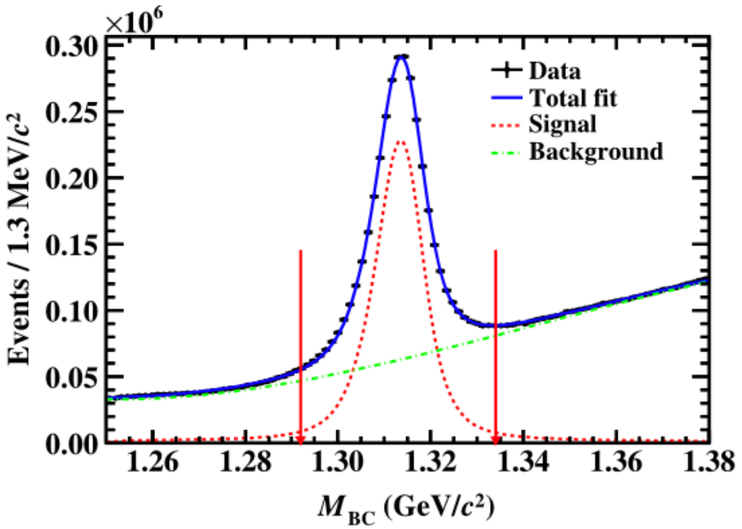
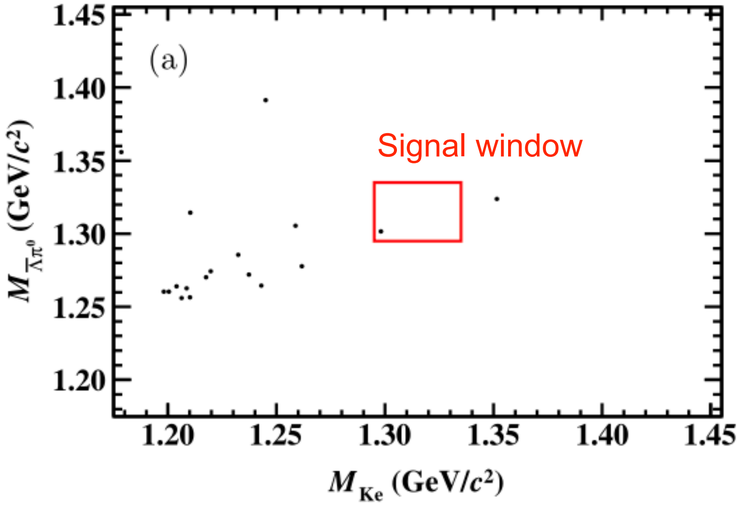
➔ Data: $(1.0087 \pm 0.0044) \times 10^{10}$ J/ψ events taken @ 3.097 GeV

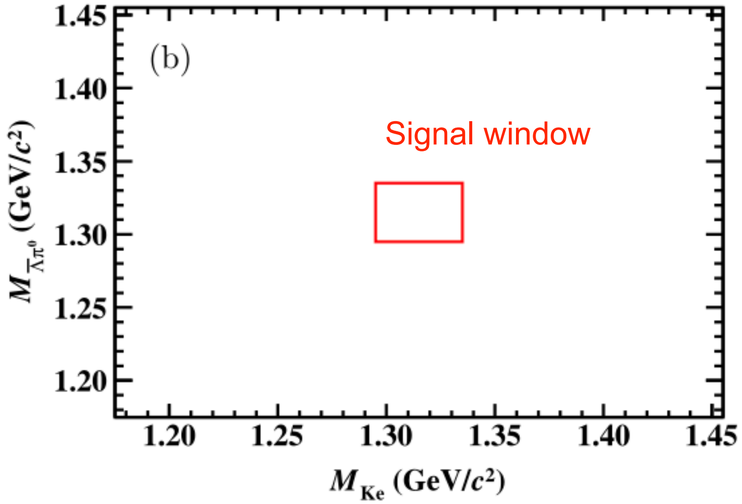
➔ $J/\psi \to \Xi^0\bar{\Xi}^0$ double tag method. Tag side $\bar{\Xi}^0 \to \bar{\Lambda}\pi^0$



$\Xi^0 \to K^-e^+$



$\Xi^0 \to K^+e^-$



$$\mathcal{B}_{\rm sig} = \frac{N^{\rm obs}_{\rm DT}}{N^{\rm obs}_{\rm ST} \cdot \epsilon_{\rm DT}/\epsilon_{\rm ST}}$$

No obvious signal is found, ULs on BFs are set at the 90% CL

$\mathcal{B}(\Xi^0 \to K^-e^+) < 3.6 \times 10^{-6}$

$\mathcal{B}(\Xi^0 \to K^+e^-) < 1.9 \times 10^{-6}$

Summary

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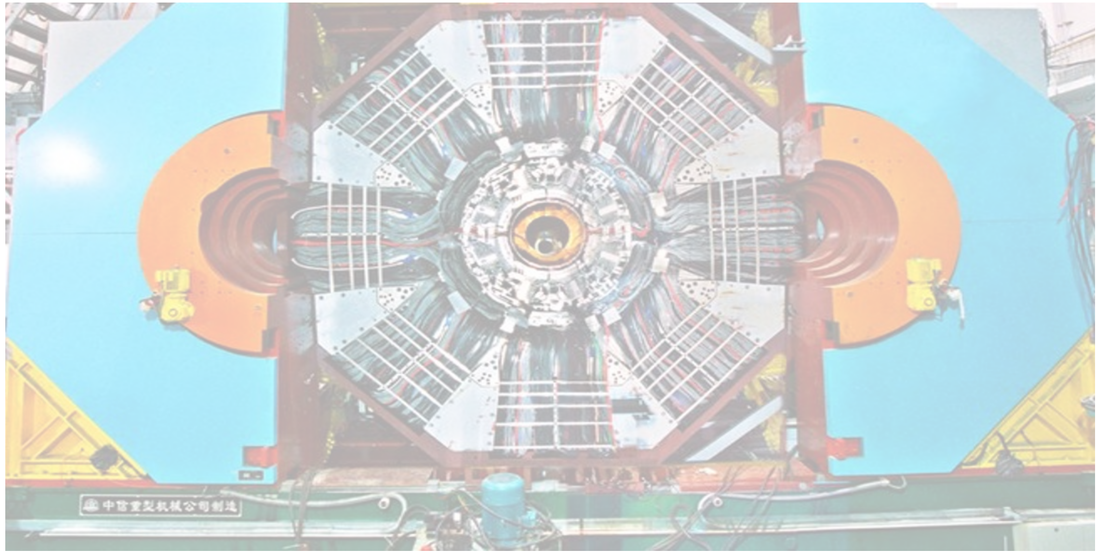
➔ The BNV/LNV processes are essential to probe New Physics beyond the Standard Model



➔ New results of BNV/LNV search at BESIII
- $\Lambda - \bar{\Lambda}$ oscillations in $J/\psi \to pK^-\bar{\Lambda}, \Lambda\bar{\Lambda}$
- $D_s^+ \to h^- h^0 e^+ e^+$
- $\omega/\phi \to \pi^+\pi^+ e^- e^-$
- $\Xi^0 \to K^\mp e^\pm$

➔ No evidence and new stringent constraint on NP

➔ BESIII has collected 10B J/ψ and 2.7B $\psi(2S)$, 20 fb^{-1} @ 3.77 GeV data and more…

➔ More results are coming soon

Thanks for your attention!

Backup

Phys. Rev. D 98, (2018) 096004