



Search for Lepton/Baryon Number Violation in Flavor Physics

Zhengyun You

Sun Yat-sen University

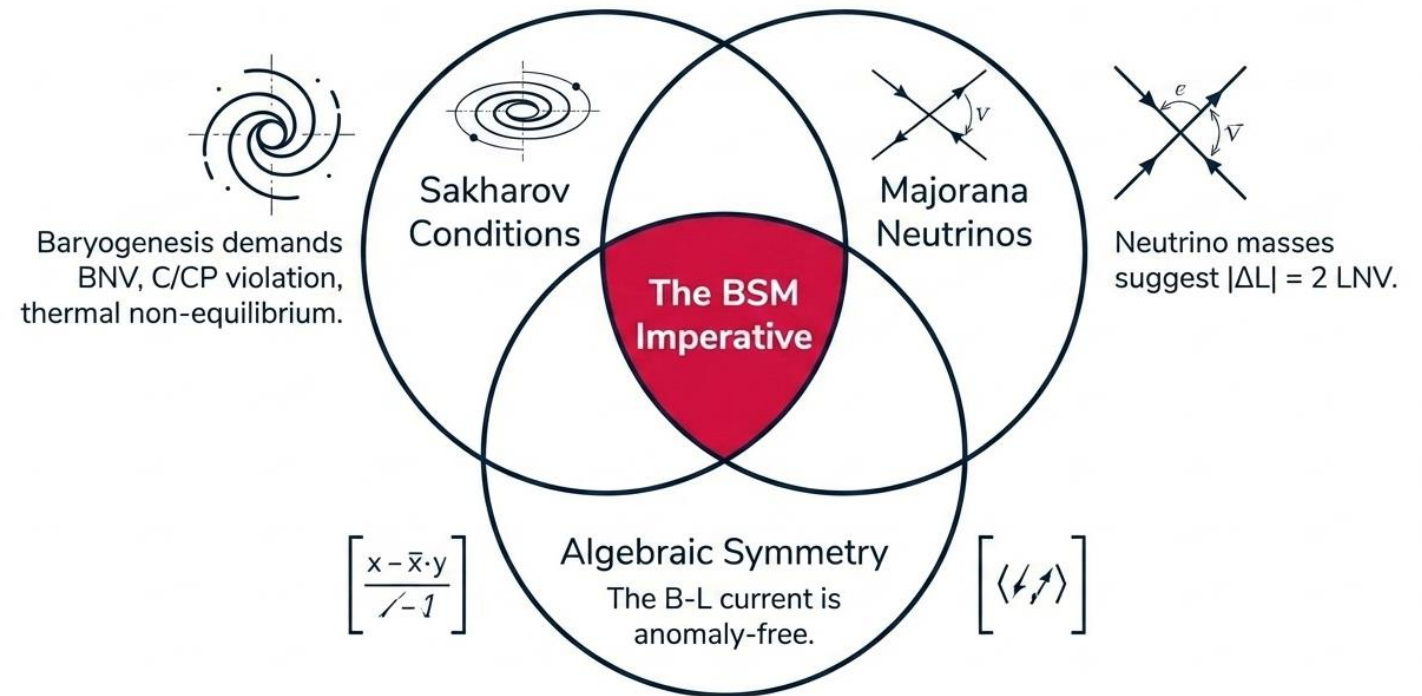
youzhy5@mail.sysu.edu.cn

Workshop on New Physics Searches at Colliders

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Outline

- Symmetries in the Standard Model
- Lepton Number Violation
- Baryon Number Violation
- Summary



Symmetries in the SM

- C, P, CP, T, CPT
- Lepton Flavor
- Quark Flavor
- Lepton Number

Lepton: $L = 1$

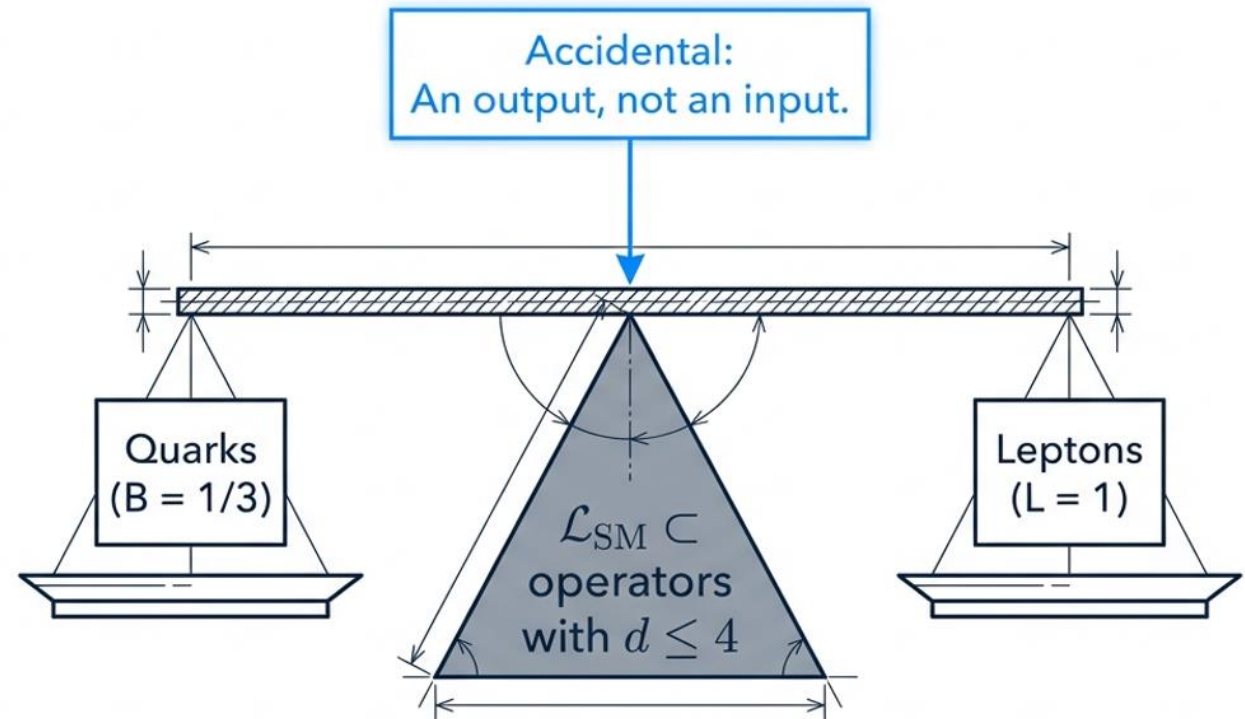
$$L = L_e + L_\mu + L_\tau$$

- Baryon Number

Quark: $B = 1/3$

Baryon: $B = 1$

Test of Conservation Laws



Particle Data Group, PHYSICAL REVIEW D **110**, 030001 (2024)



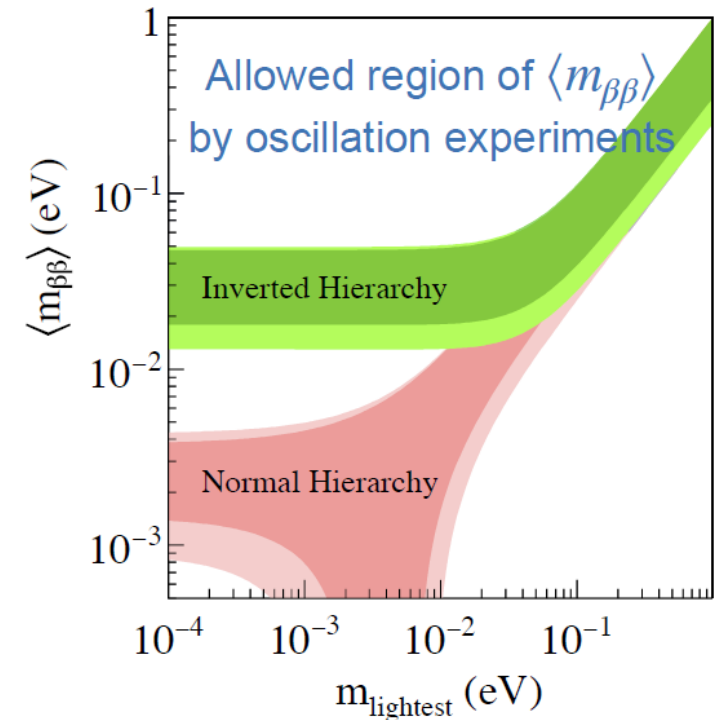
Lepton Number

- The lowest-dimension operator containing only SM fields that breaks baryon or lepton number is $\mathbf{d} = \mathbf{5}$, lepton-number-violating (LNV) ‘Weinberg’ neutrino-mass operator

$$\mathcal{L}^{\text{LNV}} = \frac{y}{\Lambda} \bar{L}^C H H^T L$$

- $\Delta L = 2$ interactions yields a **Majorana** mass for the light active neutrino
- Effective Majorana mass is one of the channels to access neutrino mass

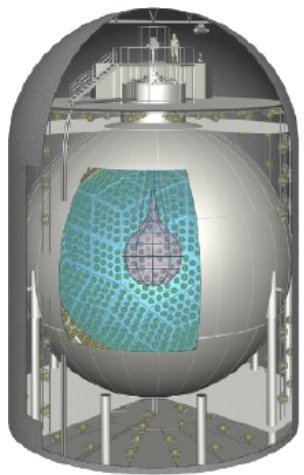
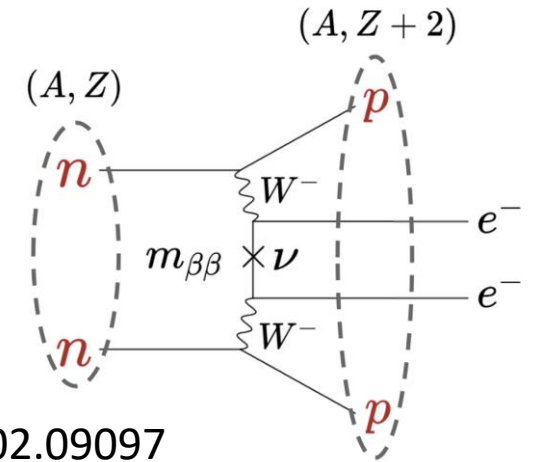
$$\left(T_{1/2}^{0\nu}\right)^{-1} = G^{0\nu} |M^{0\nu}|^2 \langle m_{\beta\beta} \rangle$$



[LamLAND-Zen, H. Miyake, PIC2024](#)

Neutrinoless Double-Beta Decay

- Search for neutrinoless double-beta decay ($0\nu\beta\beta$) of atomic nuclei
 $(Z, A) \rightarrow (Z + 2, A) + e^- + e^-$
- The current best limit, obtained by **KamLAND-Zen** with ^{136}Xe
 $\tau_{1/2} > 2.3 \times 10^{26} \text{ yr}$



KamLAND &
KamLAND-Zen

2024

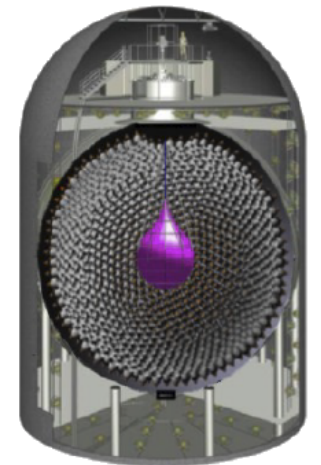
2025

2026

2027



1000 kg Xe



KamLAND2 &
KamLAND2-Zen

[LamLAND-Zen, H. Miyake, PIC2024](#)

LNV at Colliders

- The BSM interactions in the see-saw mechanism for neutrino mass

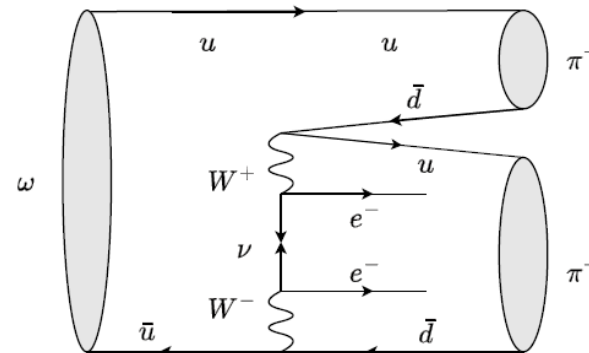
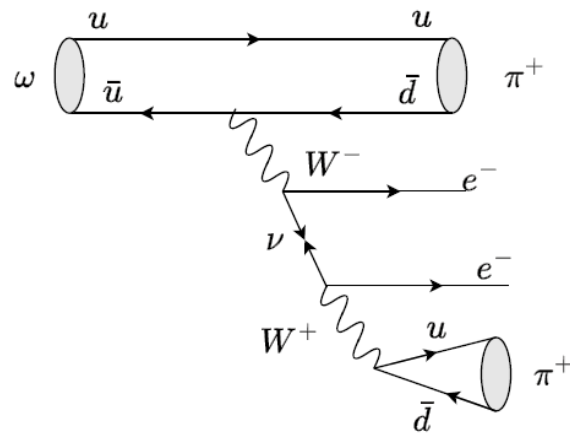
$$\Lambda \sim \text{GUT scale}, \quad \nu \text{ mass} \sim \text{eV}, \quad y \sim \text{Fermion Yukawa coupling}$$

- If LNV scale $\Lambda \sim 1 \text{ TeV}$, LNV signature at colliders

- LNV observables at colliders, **same sign dileptons**

$$Y \rightarrow X + 2e^-, Y \rightarrow X + 2\mu^+$$

- The results from colliders complement those obtained from $0\nu\beta\beta$



CPC 49, 103002 (2025)



LVN at Flavor Factories

- μ factory: SINDRUM, Mu2e, Comet, $\mu^- \text{Ti} \rightarrow e^+ \text{Ca}$
- τ factory: Babar, Belle/BelleII $\tau^- \rightarrow e^+ \pi^- \pi^-$
- K factory: NA62, KOTO, ... $K^+ \rightarrow \pi^- \mu^+ \mu^+$
- D factory: BESIII, LHCb, Belle, ... $D^+ \rightarrow \pi^- \mu^+ \mu^+$
- B factory: LHCb, Babar, Belle, ... $B^- \rightarrow \pi^+ \mu^- \mu^-$
- Provide useful bounds on the effective **Majorana** neutrino mass matrix

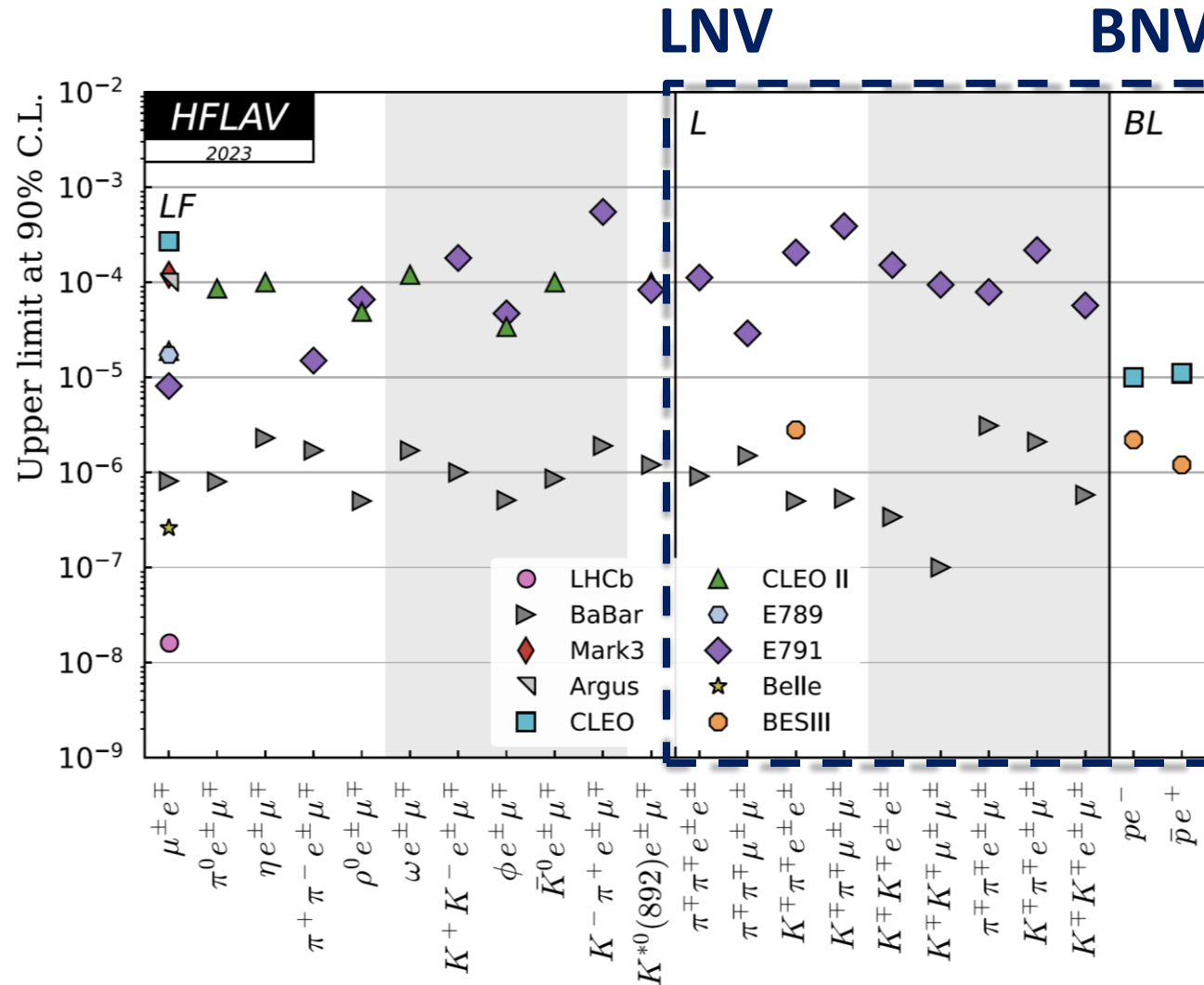
$$m_{ll'} \sim \sum_i U_{li} U_{l'i} m_{\nu_i}$$

- Although not as strong as the constraints on m_{ee} from $0\nu\beta\beta$



LNV in D^0 decay

- D^0

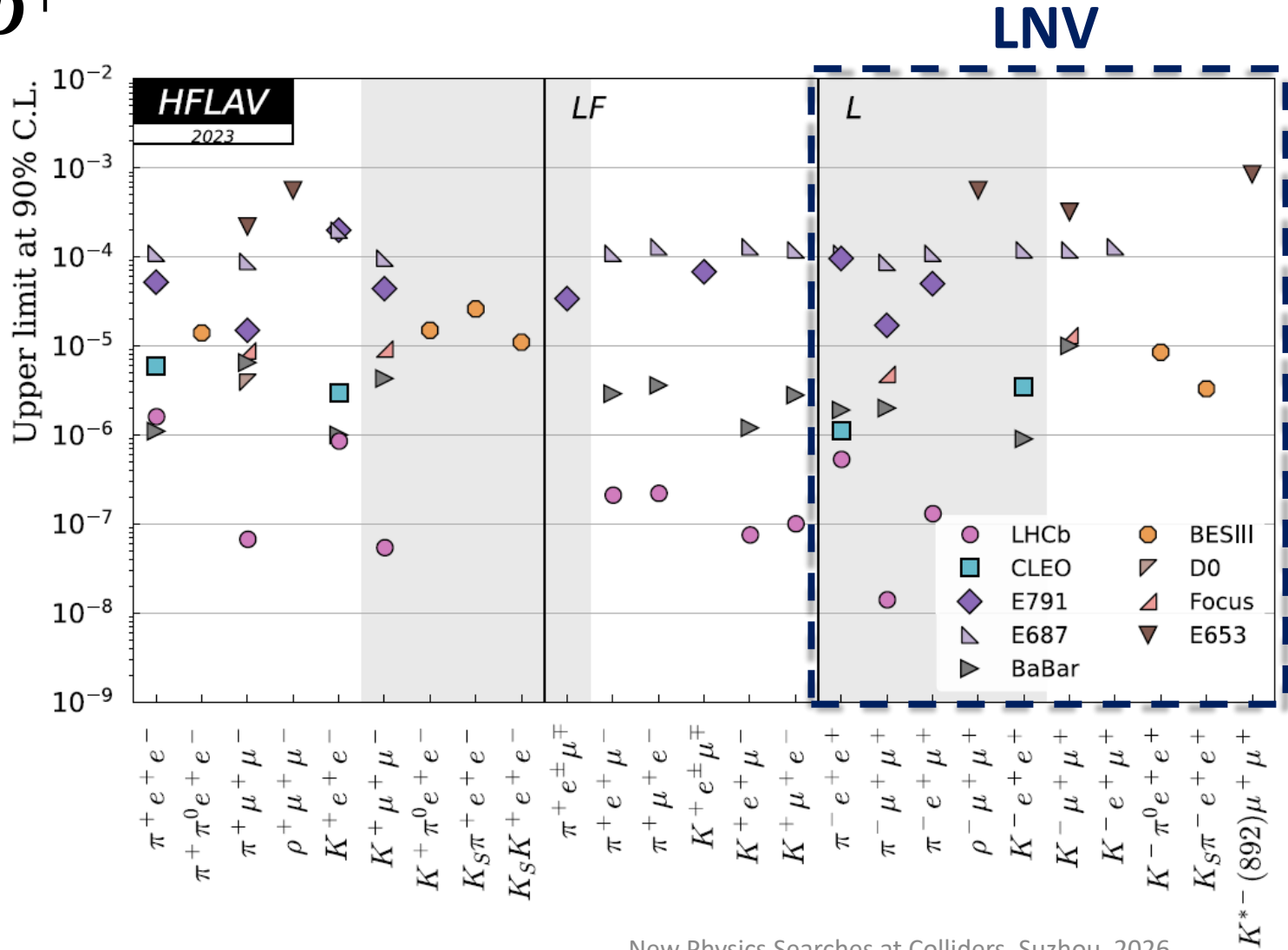


HFLAV Group, PRD **113**, 012008 (2026)



LNV in D^+ decay

- D^+



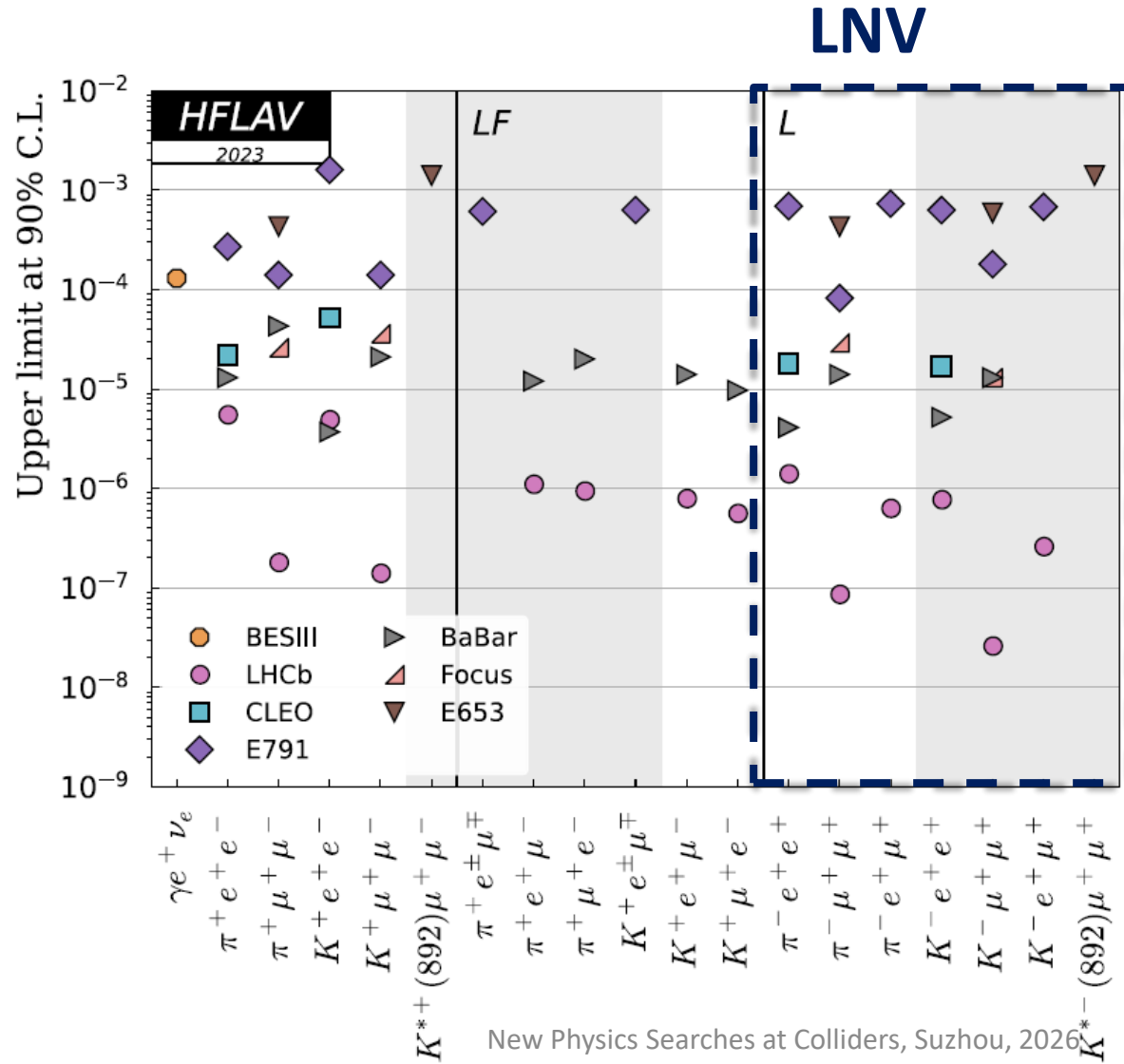
$$D^+ \rightarrow h^- l^+ l^{(\prime)+}$$

UL: $10^{-8} \sim 10^{-4}$ level



LNV in D_s^+ decay

- D_s^+



$D_s^+ \rightarrow h^- l^+ l^{(\prime)+}$
 UL: $10^{-8} \sim 10^{-4}$ level

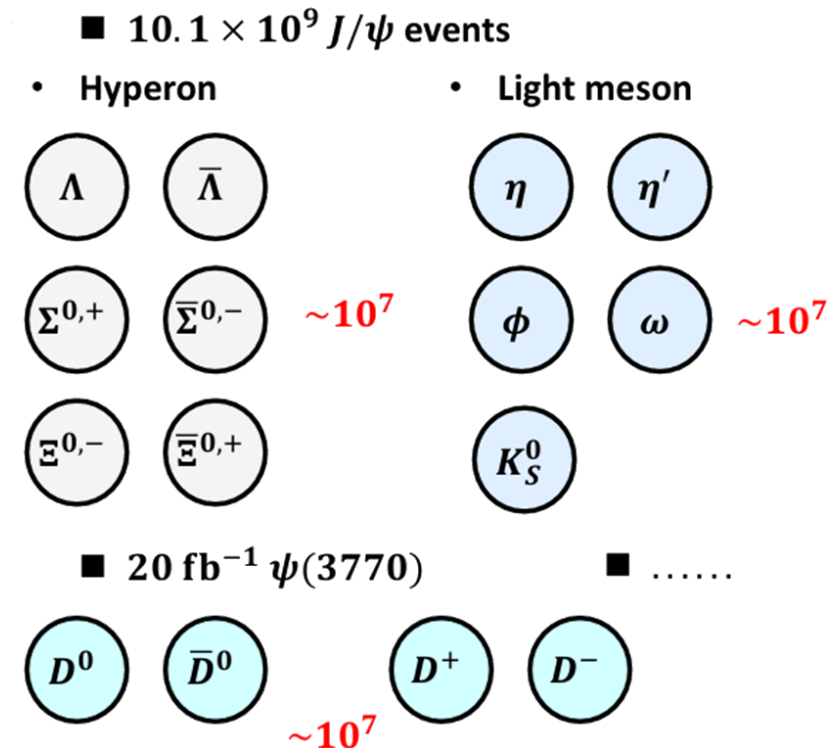


LNV at BESIII

With the $10^{10} J/\psi$ events & their intermediate decay products

The upper limits at 90% C. L.

- $\mathcal{B}(\phi \rightarrow \pi^+ \pi^+ e^- e^-) < 1.3 \times 10^{-5}$ CPC **49**, 043001 (2025)
- $\mathcal{B}(\eta \rightarrow \pi^+ \pi^+ e^- e^-) < 4.6 \times 10^{-6}$ PRD **112**, 112021 (2025)
- $\mathcal{B}(\omega \rightarrow \pi^+ \pi^+ e^- e^-) < 2.8 \times 10^{-6}$ CPC **49**, 103002 (2025)
- $\mathcal{B}(J/\psi \rightarrow K^+ K^+ e^- e^-) < 2.1 \times 10^{-9}$ CPC **50**, 013107 (2026)
- $\mathcal{B}(D_s^+ \rightarrow h^- h^0 e^+ e^+) < \sim 10^{-5}$ level JHEP **01**, 109 (2025)
- $\mathcal{B}(\Xi^- \rightarrow \Sigma^+ e^- e^-) < 2.0 \times 10^{-5}$ arXiv:2511.15394

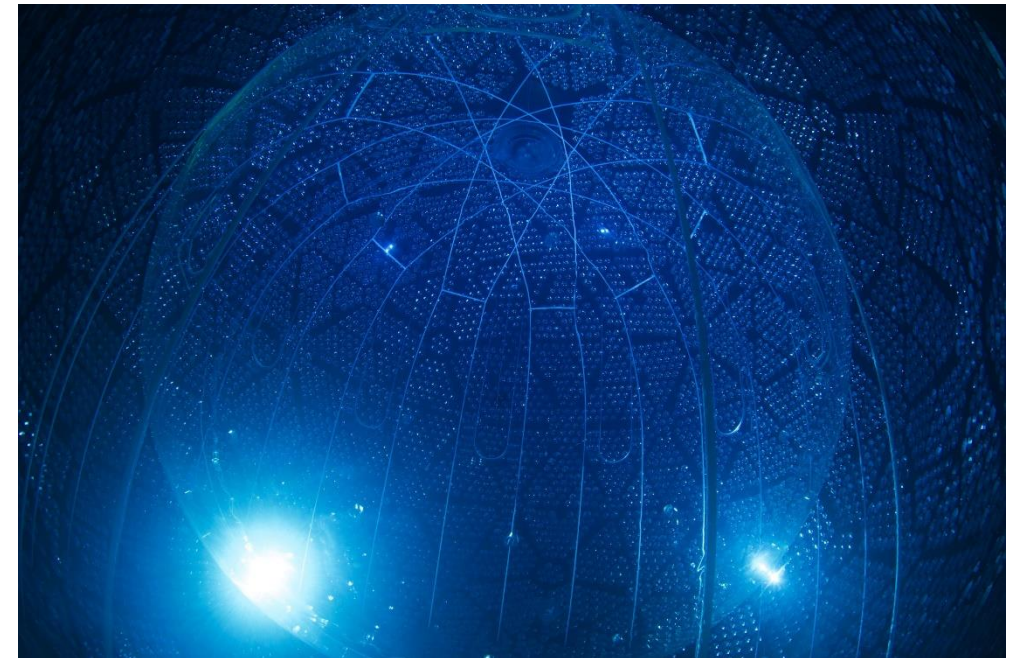
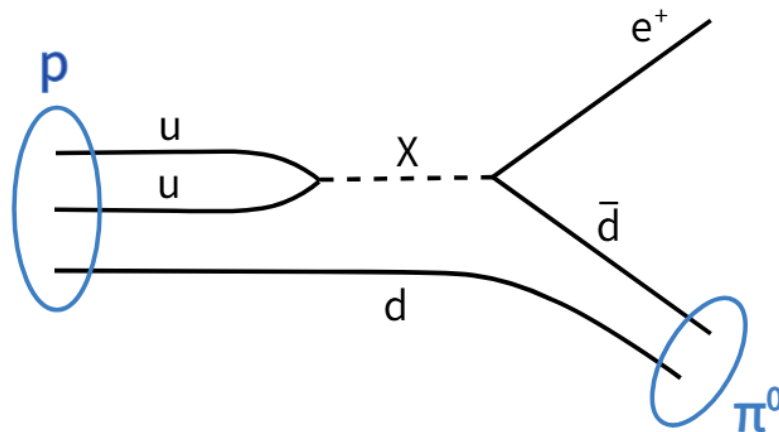


Baryon Number

- Grand Unified Theories (GUTs) combine leptons and quarks in the same symmetry multiplets
- Predict the violation of the baryon and lepton quantum numbers
- **Proton decay** @90% C. L.

SNO+: $\tau(p \rightarrow inv) > 1.1 \times 10^{29} \text{ yr}$

SuperK: $\tau(p \rightarrow e^+ \pi^0) > 2.4 \times 10^{34} \text{ yr}$

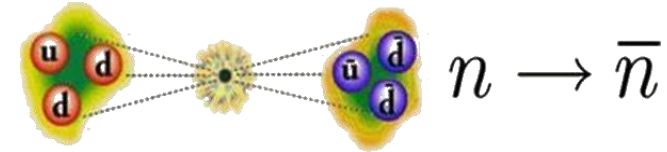


$n - \bar{n}$ Oscillation

- Experimental limits from SuperK (@90% C.L.)

Free neutron oscillation time: $\tau_{n\bar{n}} > 0.86 \times 10^8 \text{ s}$

Bound neutron (^{16}O) oscillation time: $\tau_m > 3.6 \times 10^{32} \text{ yr}$



- Effective Hamiltonian for the free (anti-)neutron

$$\langle n | \mathcal{H}_{eff} | n \rangle = \langle \bar{n} | \mathcal{H}_{eff} | \bar{n} \rangle = m - i \frac{\lambda}{2},$$

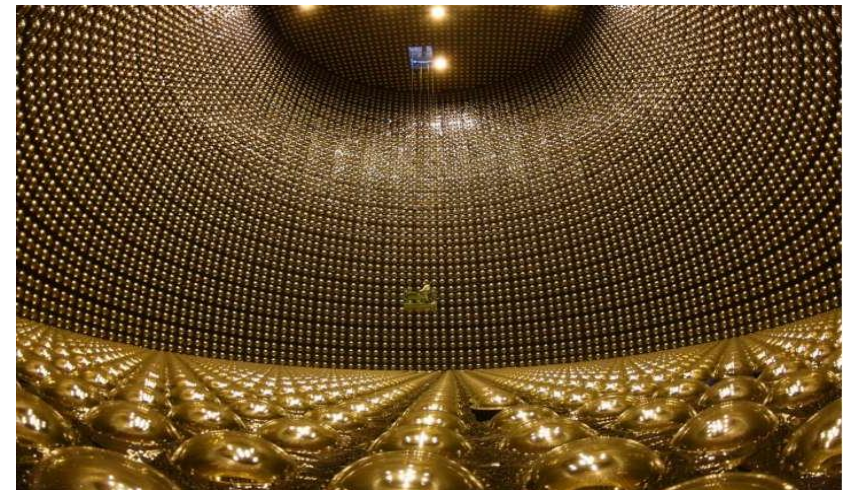
$$\langle n | \mathcal{H}_{eff} | \bar{n} \rangle = \langle \bar{n} | \mathcal{H}_{eff} | n \rangle = \delta m$$

- With CPT conserved, $\tau_n = 1/\lambda$ and $\tau_{n\bar{n}} = 1/|\delta m|$

- $n - \bar{n}$ oscillation rate $\mathcal{P}_{n\bar{n}}(t) = \sin^2\left(\frac{t}{\tau_{n\bar{n}}}\right) e^{-\lambda t},$

- For $t \ll \tau_n \ll \tau_{n\bar{n}}, \mathcal{P}_{n\bar{n}}(t) \rightarrow \left(\frac{t}{\tau_{n\bar{n}}}\right)^2$

$$n \text{ --- } \boxed{\delta m_{n\bar{n}}} \text{ --- } \bar{n}$$



Super-Kamiokande



Search for $\Lambda - \bar{\Lambda}$ Oscillation at BESIII

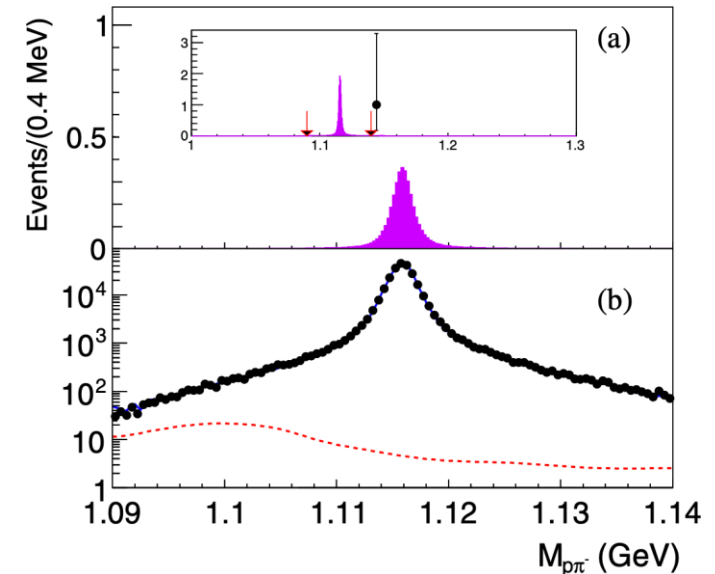
- In 2007, K.B. Luk pointed out $\Lambda - \bar{\Lambda}$ oscillation may exist
- In 2010, X.W. Kang & H.B. Li gave a prospect of searching for $\Lambda - \bar{\Lambda}$ oscillation at BESIII
- 2017, LHCb constrained on $\Xi_b^0 - \bar{\Xi}_b^0$ oscillation
- BESIII searched for $\Lambda - \bar{\Lambda}$ oscillation in



- Oscillation rate $\mathcal{P}(\Lambda) < 4.4 \times 10^{-6}$ (90% C.L.)
- Oscillation parameter

$$\delta m_{\Lambda\bar{\Lambda}} = \frac{\mathcal{P}(\Lambda)}{2\tau_{\Lambda}^2} < 3.8 \times 10^{-18} \text{ GeV (90% C.L.)}$$

PRL 131, 121801 (2023)





BNV in Particle Decays at Colliders

- For elementary particles, $n-\bar{n}$ oscillation involves $qqq \rightarrow \bar{q}\bar{q}\bar{q}$
- The lowest dimension operators at dimension 9 in SMEFT:

$$\mathcal{L}_{n-\bar{n}} = \frac{1}{\Lambda^5} \sum_j \alpha_j^{(9)} \mathcal{O}_j^{\text{BNV}}$$

- Consequently, $\delta m \sim \alpha_j^{(9)} \frac{\Lambda_{\text{HAD}}^6}{\Lambda^5}$
- $\Lambda_{\text{HAD}} \sim QCD \text{ scale}$, current $\tau_{n\bar{n}}$ bounds yields BNV mass scale of $\sim 100 \text{ TeV}$
- Search for BNV decays of short-lived particles

$$\mathcal{B}(Z \rightarrow pe, p\mu) < 1.8 \times 10^{-6}$$

$$\mathcal{B}(\tau^- \rightarrow \bar{p}\mu^- \mu^+) < 1.8 \times 10^{-8}$$

$$\mathcal{B}(B_0 \rightarrow p\mu^-) < 2.6 \times 10^{-9}$$



BNV Searches at BESIII

Decay Mode	$B_{90\%}^{UP} (\times 10^{-8})$	Publication
$\Lambda \rightarrow \bar{\Lambda}$	440	PRL131, 121801 (2023)
$\Xi^0 \rightarrow K^- e^+$	360	PRD108, 012006 (2023)
$\Xi^0 \rightarrow K^+ e^-$	190	
$D^0 \rightarrow \bar{p} e^+$	120	PRD105, 032006 (2022)
$D^0 \rightarrow p e^-$	220	
$D^+ \rightarrow \bar{n} e^+ + \text{c.c.}$	1430	PRD106, 112009 (2022)
$D^- \rightarrow p e^- + \text{c.c.}$	2920	
$D^+ \rightarrow \Lambda e^+$	110	PRD 101, 031102(2020)
$D^+ \rightarrow \bar{\Lambda} e^+$	65	
$D^+ \rightarrow \Sigma^0 e^+$	170	
$D^+ \rightarrow \bar{\Sigma}^0 e^+$	130	
$J/\psi \rightarrow \Lambda_c^+ e^-$	6.9	PRD 92, 072006(2019)



Summary

- Symmetries and their violation play key roles in the SM
- Discovery of LNV/BNV would represent a groundbreaking milestone
- Experiments of intensity frontiers, Belle II, LHCb, BESIII, ... has contributed a lot in LNV/BNV searches
- More to expect in the future

Thank you!