Status of Proton Decay Searches

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based on our Snowmass NF03 Whitepaper **arXiv:2203.08771 [hep-ex]**

CONFERENCE ON SCIENCE AT THE
SANFORD UNDERGROUND RESEARCH FACILITY

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Thanks to all the contributors

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on the Future of Particle Physics (Snowmass 2021)

Searches for Baryon Number Violation in Neutrino Experiments: A White Paper

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A diverse group of 38 people from 31 institutions

Outline

- Motivation
- Proton Decay: Past, Present and Future
    - Theory
    - Lattice
    - Experiments
- Other BNV Processes (e.g. $n - \bar{n}$)
- Far-reaching BSM Implications
- Conclusion

[Figure from Symmetry Magazine]

Motivation

- Electron is stable because of electric charge conservation.
- But proton stability is not guaranteed by any fundamental symmetry.
- In the SM, proton is stable due to an accidental global symmetry of baryon number (and $B-L$). [Weyl '29; Stückelberg '38; Wigner '49]
- Not respected in UV-complete theories of quark-lepton symmetry, like GUTs.

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- Also, B violation is an essential ingredient for baryogenesis. [Sakharov (JETP '67)]

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Violation of *CP* invariance, *C* asymmetry, and baryon asymmetry of the universe

A. D. Sakharov

(Submitted 23 September 1966)
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Also S7, pp. 85–88]

The strong violation of the baryon charge during the superdense state and the fact that the baryons are stable in practice do not contradict each other. Let us consider a concrete model. We introduce interactions of two types.

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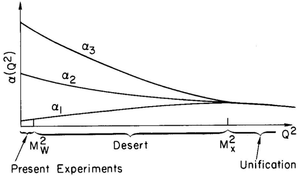
Unification and baryogenesis provide natural motivations for $B\!\!\!/$ searches.

Historical Context

- **Grand Unification** of strong, weak and electromagnetic interactions at $Q \gtrsim M_X \gg M_Z$. [Pati, Salam (PRL '73); Georgi, Glashow (PRL '74)]
- Consequence: Proton decay mediated by new gauge bosons which couple to both quarks and leptons.
- Dimension-6 operator: Amplitude $\propto 1/M_X^2$ or decay rate $\propto 1/M_X^4$.
- Lifetime: $\tau_p \sim \frac{16\pi^2 M_X^4}{g_{\mathrm{GUT}}^4 m_p^5} \sim 10^{30}$ yr for $M_X \sim 10^{14}$ GeV.
- 10^{30} nucleons $\sim$ 20 ton of water.
- Original idea behind Kamiokande (Kamioka Nucleon Decay Experiment).
- Subsequently upgraded to Super-Kamiokande (several kt water).



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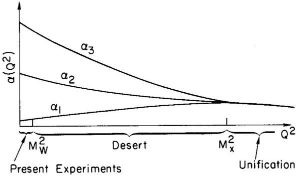

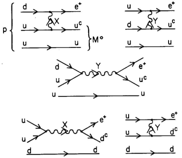

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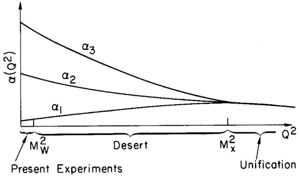

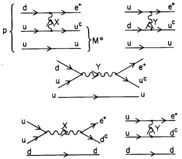

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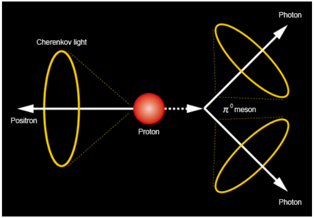
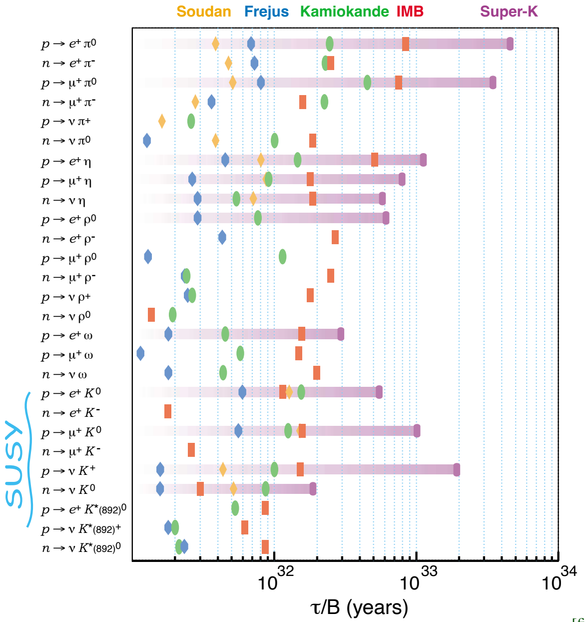
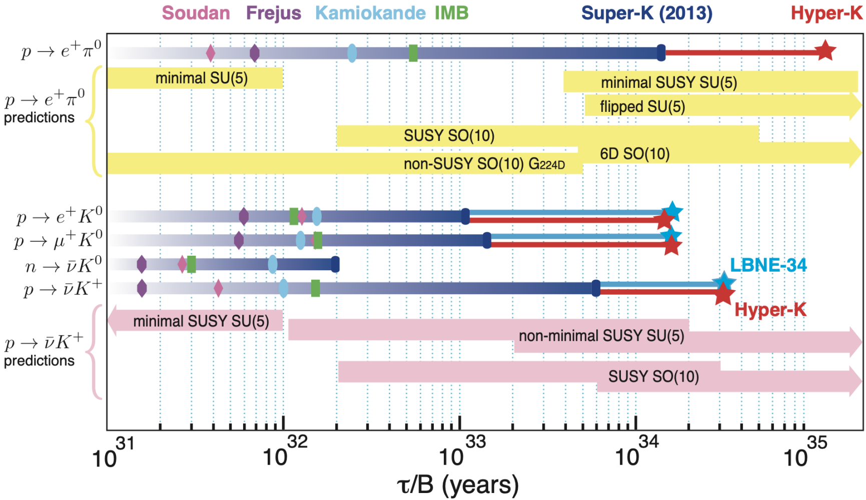


Experimental Status (Snowmass 2001)



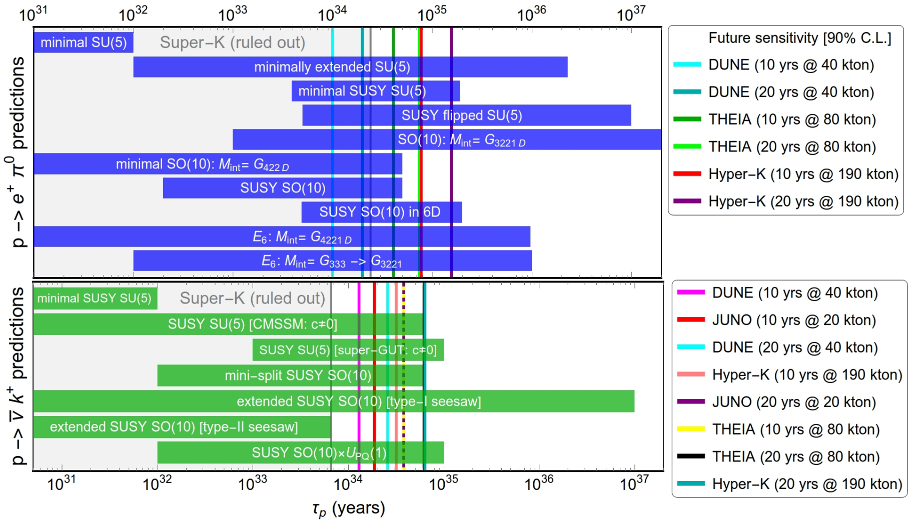
[figure courtesy Ed Kearns]

Experimental Status (Snowmass 2013)



[Hewett et al, 1401.6077]

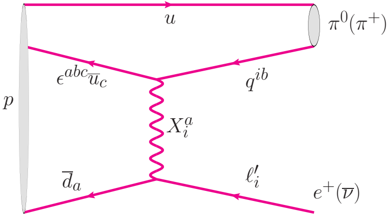
Experimental Status (Snowmass 2021)

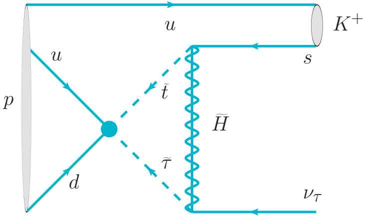


[BD, Koerner, Saad et al, 2203.08771]

Please see the proton decay parallel session this afternoon for the experimental details.

Dominant Proton Decay Modes





Modes (partial lifetime)	Current limit [90% CL] (10^{34} years)	Future Sensitivity [90% CL] (10^{34} years)
$\tau_p\left(p \to e^+\pi^0\right)$	Super-K: 2.4 [55]	Hyper-K (1900 kton-yrs): 7.8 [56] DUNE (400 kton-yrs): ~1.0 [57] THEIA (800 kton-yrs): 4.1
$\tau_p\left(p \to \mu^+\pi^0\right)$	Super-K: 1.6 [55]	Hyper-K (1900 kton-yrs): 7.7 [56]
$\tau_p\left(p \to \overline{\nu}K^+\right)$	Super-K: 0.66 [58]	Hyper-K (1900 kton-yrs): 3.2 [56] DUNE (400 kton-yrs): 1.3 [59] JUNO (200 kton-yrs): 1.9 [60] THEIA (800 kton-yrs) 3.8
$\tau_p\left(p \to \overline{\nu}\pi^+\right)$	Super-K: 0.039 [61]	–

[BD, Koerner, Saad et al, 2203.08771]

Theory Predictions (Non-SUSY Models)

Model	Decay modes	τ_N $(N = p, n)$ [years]	Ref.
Non-SUSY minimal $SU(5)$	$p \to e^+\pi^0$	$10^{30} - 10^{32}$	Georgi, Glashow [16]
Non-SUSY minimally extended $SU(5)$ (neutrino mass: 1-loop)	$p \to e^+\pi^0$	$\lesssim 2.3 \times 10^{36}$	Doršner, Saad [82]
Non-SUSY minimally extended $SU(5)$ (neutrino mass: 1-loop)	$p \to e^+\pi^0$ $p \to \overline{\nu}K^+$	$10^{32} - 10^{36}$ $10^{34} - 10^{37}$	Perez, Murgui [74]
Non-SUSY Minimal $SU(5)$ [NR] (neutrino mass: type-II seesaw)	$p \to \nu + (K^+, \pi^+, \rho^+)$ $n \to \nu + (\pi^0, \rho^0, \eta^0, \omega^0, K^0)$	$10^{31} - 10^{38}$	Doršner, Perez [64]
Non-SUSY Minimal $SU(5)$ [NR] (neutrino mass: type-III+I seesaw)	$p \to e^+\pi^0$	$\lesssim 10^{36}$	Bajc, Senjanović [65]
Non-SUSY Extended $SU(5)$ (neutrino mass: 2-loop)	$p \to e^+\pi^0$	$10^{34} - 10^{40}$	Saad [80]
Minimal flipped non-SUSY $SU(5)$	$p \to e/\mu^+\pi^0$	$10^{38} - 10^{42}$	Arbeláez, Kolešová, Malinský [175]
Non-SUSY Minimal $SO(10)$	$p \to e^+\pi^0$	$\lesssim 5 \times 10^{35}$	Babu, Khan [165]
Minimal $SO(10)$ with 45 Higgs	$p \to e^+\pi^0$	$\lesssim 10^{36}$	Bertolini, Di Luzio, Malinský [176]
Minimal non-Renormalizable $SO(10)$	$p \to e^+\pi^0$	$\lesssim 10^{35}$	Preda, Senjanović, Zantedeschi [173]
Non-SUSY Generic $SO(10)$ $M_{\text{int}} : G_{422}$ $M_{\text{int}} : G_{422D}$ $M_{\text{int}} : G_{3221}$ $M_{\text{int}} : G_{3221D}$	$p \to e^+\pi^0$	 $10^{34} - 10^{46}$ $10^{31} - 10^{34}$ $10^{36} - 10^{46}$ $10^{33} - 10^{43}$	Chakrabortty, King, Maji [164]
Non-SUSY Generic E_6 $M_{\text{int}} : G_{4221}$ $M_{\text{int}} : G_{4221D}$ $M_{\text{int}} : G_{333} \to G_{3221}$ $M_{\text{int}} : G_{4221D} \to G_{421}$ $M_{\text{int}} : G_{4221} \to G_{421}$	$p \to e^+\pi^0$	 $10^{27} - 10^{36}$ $10^{27} - 10^{36}$ $10^{32} - 10^{36}$ $10^{26} - 10^{48}$ $10^{25} - 10^{48}$	Chakrabortty, King, Maji [164]

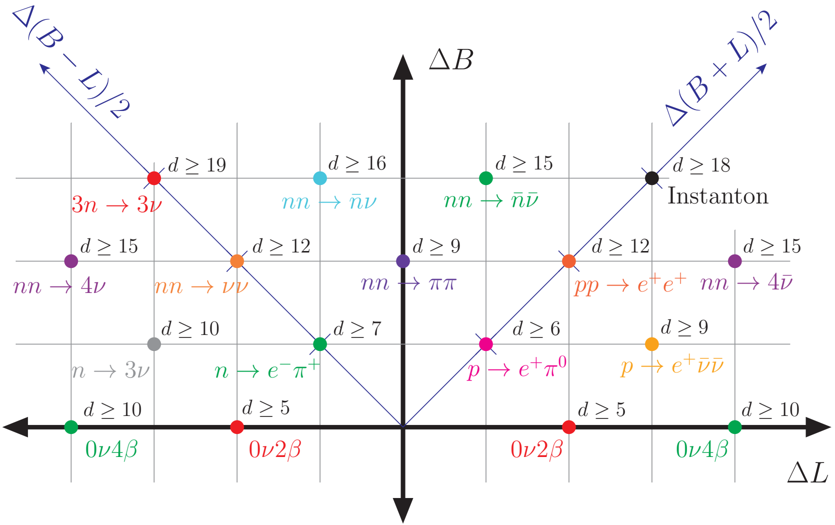
[BD, Koerner, Saad et al, 2203.08771]

Theory Predictions (SUSY Models)

Model	Decay modes	τ_N $(N = p, n)$ [years]	Ref.
Minimal SUSY $SU(5)$	$p \to \bar{\nu} K^+$ $n \to \bar{\nu} K^0$	$10^{28} - 10^{32}$	Dimopoulos, Georgi [42], Sakai [100] Hisano, Murayama, Yanagida [99]
Minimal SUSY $SU(5)$ (cMSSM)	$p \to \bar{\nu} K^+$ $p \to e^+ \pi^0$	$\lesssim (2-6) \times 10^{34}$ $10^{35} - 10^{40}$	Ellis et. al. [107]
Minimal SUSY $SU(5)$ ($\mathbf{5} + \overline{\mathbf{5}}$ matter fields)	$p \to \bar{\nu} K^+$ $p \to \mu^+ \pi^0 / K^0, n \to \bar{\nu} \pi^0 / K^0$	$\lesssim 4 \times 10^{33}$ $10^{33} - 10^{34}$	Babu, Bajc, Tavartkiladze [177]
SUGRA $SU(5)$	$p \to \bar{\nu} K^+$	$10^{32} - 10^{34}$	Nath, Arnowitt [103, 178]
mSUGRA $SU(5)$ (Higgs mass constraint) NUSUGRA $SU(5)$ (Higgs mass constraint)	$p \to \bar{\nu} K^+$ $p \to \bar{\nu} K^+$	$3 \times 10^{34} - 2 \times 10^{35}$ $3 \times 10^{34} - 10^{36}$	Liu, Nath [111]
SUSY $SU(5)$ or $SO(10)$ MSSM $(d = 6)$	$p \to e^+ \pi^0$	$\sim 10^{34.9 \pm 1}$	Pati [179]
Flipped SUSY $SU(5)$ (cMSSM)	$p \to e/\mu^+ \pi^0$	$10^{35} - 10^{37}$	Ellis et. al. [180–182]
Split SUSY $SU(5)$	$p \to e^+ \pi^0$	$10^{35} - 10^{37}$	Arkani-Hamed, et. al. [183]
SUSY $SU(5)$ in 5D	$p \to \mu^+ K^0$ $p \to e^+ \pi^0$	$10^{34} - 10^{35}$	Hebecker, March-Russell[184]
SUSY $SU(5)$ in 5D variant II	$p \to \bar{\nu} K^+$	$10^{36} - 10^{39}$	Alciati et.al.[185]
Mini-split SUSY $SO(10)$	$p \to \bar{\nu} K^+$	$\lesssim 6 \times 10^{34}$	Babu, Bajc, Saad [146]
SUSY $SO(10) \times U(1)_{\rm PQ}$	$p \to \bar{\nu} K^+$	$10^{33} - 10^{35}$	Babu, Bajc, Saad [147]
Extended SUSY $SO(10)$ Type-I seesaw Type-II seesaw Inverse seesaw	$p \to \bar{\nu} K^+$	 $10^{30} - 10^{37}$ $\lesssim 6.6 \times 10^{33}$ $\lesssim 10^{34}$	 Mohapatra, Severson [186] Mohapatra, Severson [186] Dev, Mohapatra [187]
SUSY $SO(10)$ with anomalous flavor $U(1)$	$p \to \bar{\nu} K^+$ $n \to \bar{\nu} K^0$ $p \to \mu^+ K^0$	$10^{32} - 10^{35}$	Shafi, Tavartkiladze [188]
SUSY $SO(10)$ MSSM	$p \to \bar{\nu} K^+$ $n \to \bar{\nu} K^0$	$10^{33} - 10^{34}$ $10^{32} - 10^{33}$	Lucas, Raby [189], Pati [179]
SUSY $SO(10)$ ESSM	$p \to \bar{\nu} K^+$	$10^{33} - 10^{34}$ $\lesssim 10^{35}$	Pati [179]
SUSY $SO(10)/G(224)$ MSSM or ESSM (new $d = 5$)	$p \to \bar{\nu} K^+$ $p \to \mu^+ K^0$	$\lesssim 2 \cdot 10^{34}$ $B \sim (1-50)\%$	Babu, Pati, Wilczek [190–192], Pati [179]
SUSY $SO(10) \times S_4$	$p \to \bar{\nu} K^+$	$\lesssim 7 \times 10^{33}$	Dev, Mohapatra, Dutta, Severson [193]
SUSY $SO(10)$ in 6D	$p \to e^+ \pi^0$	$10^{34} - 10^{35}$	Buchmuller, Covi, Wiesenfeldt [194]
GUT-like models from Type IIA string with D6-branes	$p \to e^+ \pi^0$	$\sim 10^{36}$	Klebanov, Witten [195]

[BD, Koerner, Saad et al, 2203.08771]

Other B Violating Modes



[Heeck, Takhistov (PRD '20)]

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So why not -

n ⟷ (New physics) ⟷ $\bar{n}$?

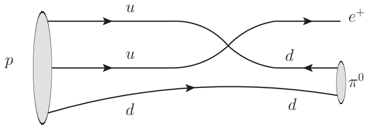
Connected with the Majorana nature of neutrino mass. [Mohapatra, Marshak (PRL '80)]

$\Delta B = 1$ versus $\Delta B = 2$

$\Delta B = 1$

- Proton decay
- Induced by dimension-6 operator $QQQL$.
- Amplitude $\propto \Lambda^{-2}$.
- $\tau_p \gtrsim 10^{34}$ yr implies $\Lambda \gtrsim 10^{15}$ GeV.
- Proton decay requires GUT-scale physics.

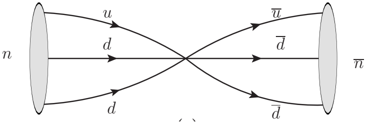
[Nath, Perez (Phys. Rep. '07)]

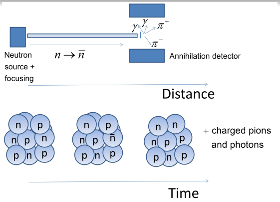


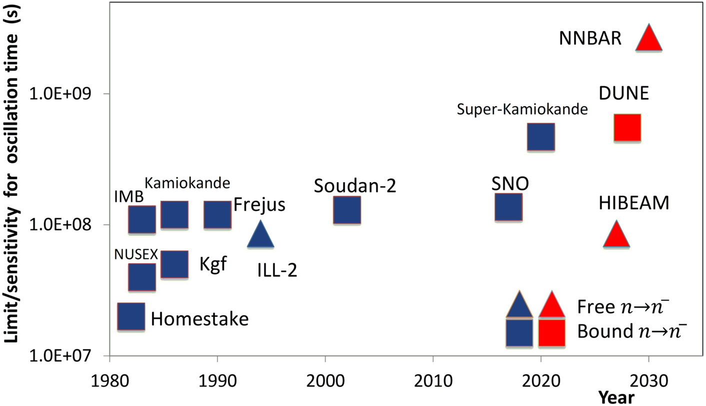
$\Delta B = 2$

- Di-nucleon decay and $n - \bar{n}$
- Induced by dimension-9 operator $QQQQQQ$.
- Amplitude $\propto \Lambda^{-5}$.
- $\Lambda \gtrsim 100$ TeV enough to satisfy experimental constraints ($\tau_{n\bar{n}} \gtrsim 10$ yr).
- $n - \bar{n}$ oscillation (and conversion) could come from a TeV-scale new physics.

[Phillips et al. (Phys. Rep '16)]



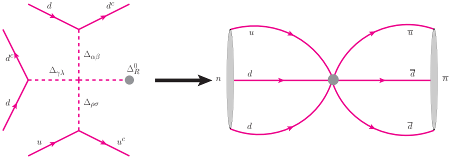




[Addazi, BD et al. (JPG '21)] See talk by Daisy Kalra this afternoon

Theoretical Upper Limit

- UV-complete embedding in Pati-Salam partial unification with $SU(4)_c \times SU(2)_L \times SU(2)_R$. [Mohapatra, Marshak (PRL '80); Babu, BD, Mohapatra (PRD '08)]



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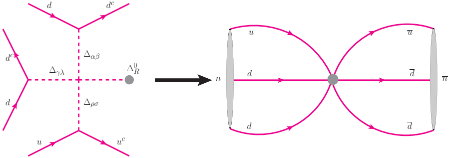
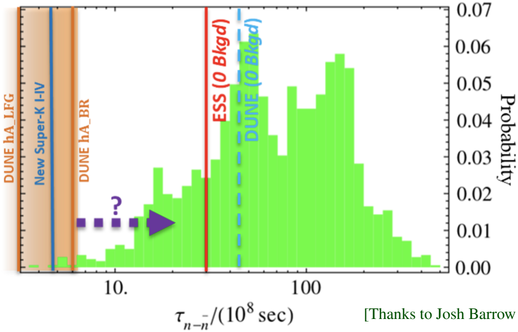
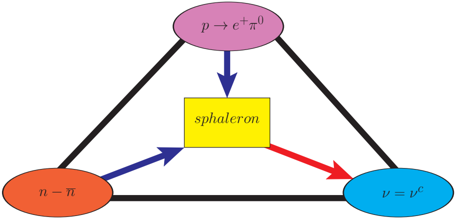


- A concrete realization of **post-sphaleron baryogenesis**. [Babu, Mohapatra, Nasri (PRL '06)]
- Leads to an *absolute upper limit* on the $n - \bar{n}$ oscillation time. [Babu, BD, Fortes, Mohapatra (PRD '13)]



[Thanks to Josh Barrow for the experimental lines]

BSM Implications



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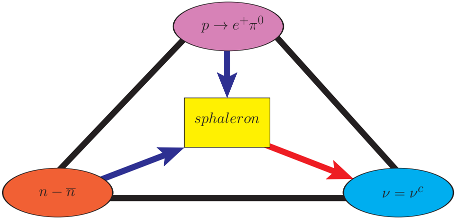
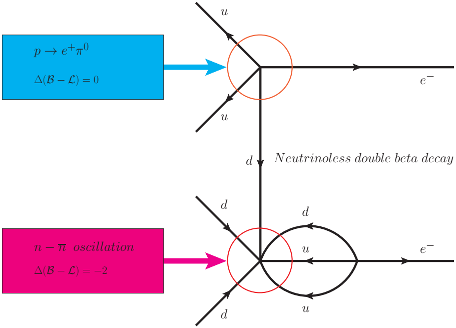
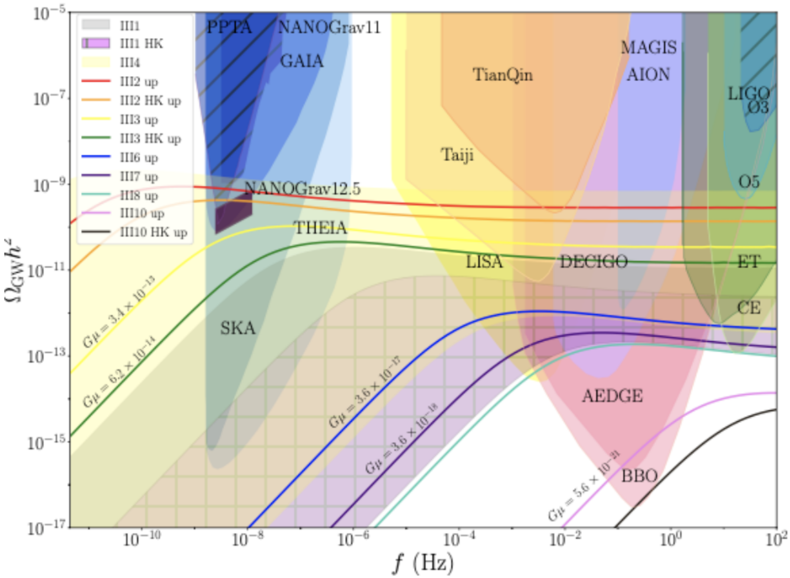




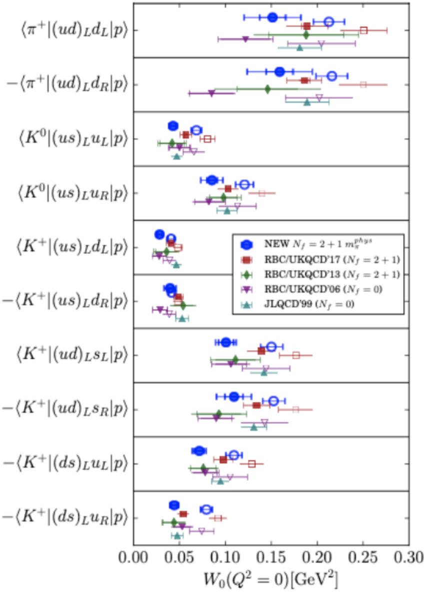
[Babu, Mohapatra (PRD '15)]

Connection to Gravitational Waves



[King, Pascoli, Turner, Zhou (JHEP '21)]

Lattice Developments



[Yoo, Aoki, Boyle, Izubuchi, Soni, Syritsyn (PRD '22)]

Conclusion

- Observation of BNV will be a clear signal of BSM physics.
- The best limits come from large-scale neutrino experiments like Super-K.
- Expected nucleon lifetimes in a wide class of GUT models are within reach of current and future (underground) experiments.
- Important to study as many BNV channels as possible.
- In particular, neutron-antineutron oscillation should be treated with the same level of importance as proton decay.
- Connection to other BSM physics: neutrino mass, baryogenesis, dark matter, gravitational waves, flavor physics.

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Thank You!