An overview of some recent theory developments in Neutron oscillations

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"Workshop on. Baryon violation by 2 units"

ACFI, August 3-6, 2020

Why search for B-violation ($\cancel{B}$)

- There are many good reasons to think that baryon and lepton number are violated in nature e.g.:

(i) Understanding the origin of matter in the universe using Sakharov's conditions;

(ii) Many beyond the standard model theories predict specific kinds of B-violation ($\cancel{B}$);

(iii) Standard model itself breaks B nonperturbatively via sphalerons

Two Major classes of $\cancel{B}$

- Proton decay : $\Delta B = 1$

(probes high scale physics and if discovered will strengthen the case for grand unified theory of forces and matter)

- Neutron-anti-neutron oscillation: $\Delta B = 2$

(Probes physics in the 1-100 TeV scale range, testable in colliders unlike p-decay

P-decay vs N-N-bar osc.

- GUTs generically predict canonical p-decay $p \rightarrow e^+ \pi^0, K^+ \bar{\nu}$; p life time model dependent. Scales like $\sim M^{-4}$

- N-N-bar predicted in theories with Majorana neutrino when extended to quark lepton unification; nn-bar oscillation time scales like $\sim M^{-5}$. May also exist in some GUT models at observable levels.

NN-bar oscillation directly connected to origin of matter! Provides an additionl handle on testing it !

Canonical Proton decay in GUTs not connected to baryogenesis ! Does not lead to baryon asymmetry!

Phenomenology for free and bound neutrons,

Key parameter Oscillation time τ:

Facts: free n: $\tau > 8.7\text{x}10^7$ sec.(ILL)

Super-K : for bound n→ $\tau > 3.5 \times 10^8$ sec.

ESS possible improvement by ~30 (very important)

Case for free NNbar vs bound NNbar:

(i) How far does the sensitivity of bound NNbar go: atmospheric bg? (Barrow's talk)

(ii) To put bounds on LIV and equivalence principle etc. need free NNbar. Bound NNbar not useful! (Babu, RNM'16)

(iii) Nuclear effects

Some recent theory developments

Three classes of nn-bar theories

- Diquark Higgs mediation:

- Majorana Fermion mediation

- 5-D models, (Shrock, Nussinov; Girmohanta, Shrock).

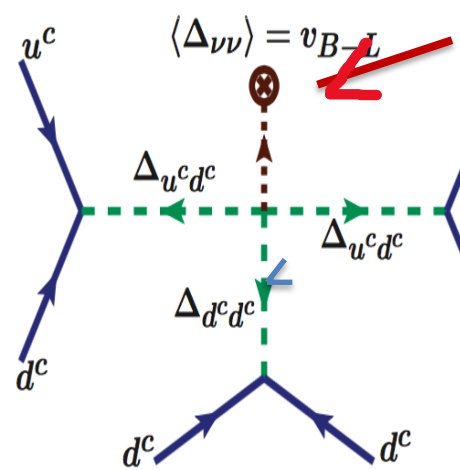
(I) N-N BAR FROM DI-QUARK HIGGS AND NEUTRINO MASS CONNECTION

- Diquark theories connect Majorana neutrinos with nn-bar when extended to quark lepton unification; (RNM, MARSHAK'80)
- In left-right models,

$$Q = I_{3L} + I_{3R} + \frac{B-L}{2}$$

Baryon and lepton numbers are connected: $\Delta L = 2$ nu mass connected to $\Delta B = 2$

m_ν

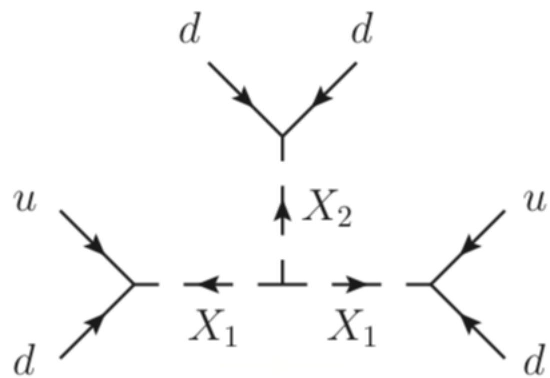


$n - \bar{n}$

- With Diquarks scalars in TeV -10 TeV scale, makes $n - \bar{n}$ observable: synergy with collider physics:

Phenomenological diquark models

- Generic diquark theories without necessarily any connection to neutrinos, see (Arnold, Fornal, Wise: Gu, Sarkar; Gardner,Yan)

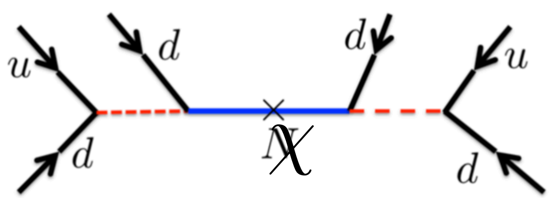


- nn-bar diquark theory can arise from SO(10) : compatible with GUTs (Babu, RNM'12)
- Current LHC bounds on diquark higgs: ~3 TeV

(ii) Majorana Fermion model

- Effective RR interaction: $\frac{1}{\Lambda^2}\chi u_a d_b d_c$ (d_b = d; d_c= d, b)

- Majorana χ leads to NNbar osc.
- Diproton decay: pp→KK,$\pi\pi$ strongly constrain these theories



- (Babu, RNM, Nasri'07; Dev, RNM'15; Mckeen, Nelson'16; Dev, Allaverdi, Dutta'17; Grojean, Wells,Sakya,Zhang'18;)
- Two parameter model: **M_χ and Λ**: M_χ >10 TeV with Λ> PeV implied by current nn-bar limit.

What is the χ Particle?

- It could be

(i) dark matter,

(ii) SUSY particle Gluino, Neutralino

(iii) Right handed neutrino, N

Can χ be identified with the Right handed neutrino?

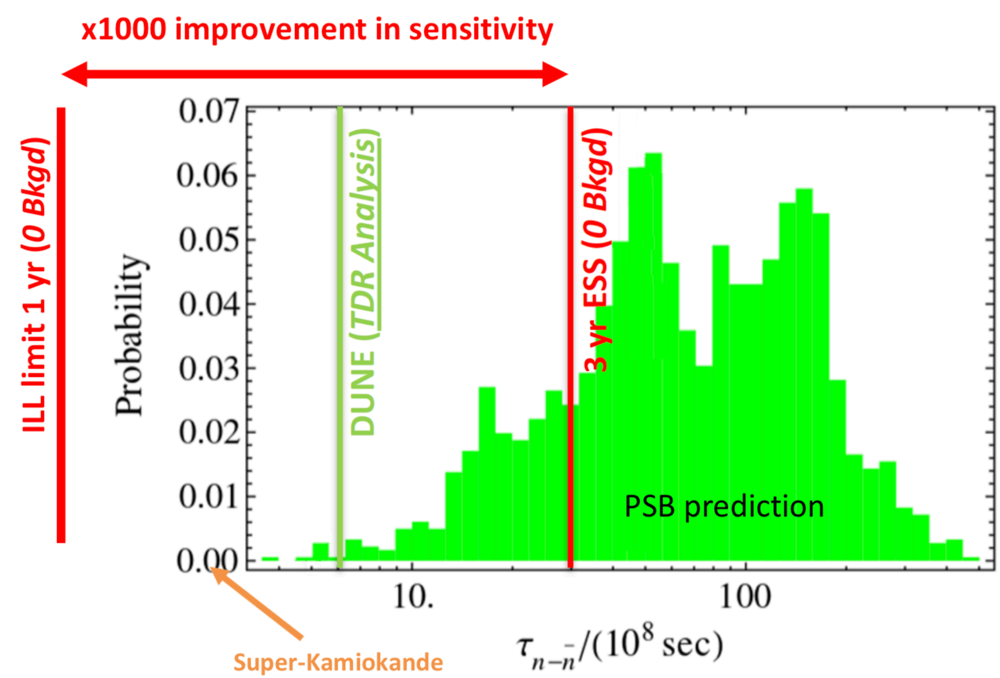
- Such theories more strongly constrained due to its connection to light nu, if nn-bar is to be observable;

- If N-nu mix to give type I seesaw → nu Dirac mass term leads to rapid proton decay if $n\bar{n}$ observable

- One way to avoid this and have n-$\bar{n}$ observable: is to generate neutrino mass via radiative seesaw (Ma) so neutrino Dirac mass is forbidden. (Dev, RNM'2015)

Origin of matter with Nnbar: Diquark Th.

- Post-sphaleron baryogenesis via S→6q decay+CPV (Babu, Mohapatra, Nasri'2006)
- Works in diquark exchange models for nn-bar: PSB testable in the next generation nn-bar search: (Babu, Dev, Fortes, RNM'13)



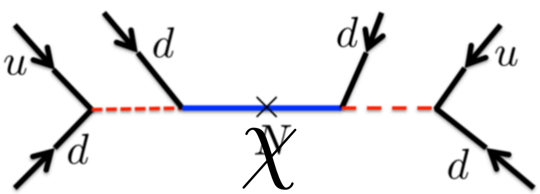
- (Babu's talk; B. Dev's talk)
- (Broussard's talk at BLV2020)

Testing PSB with neutron EDM

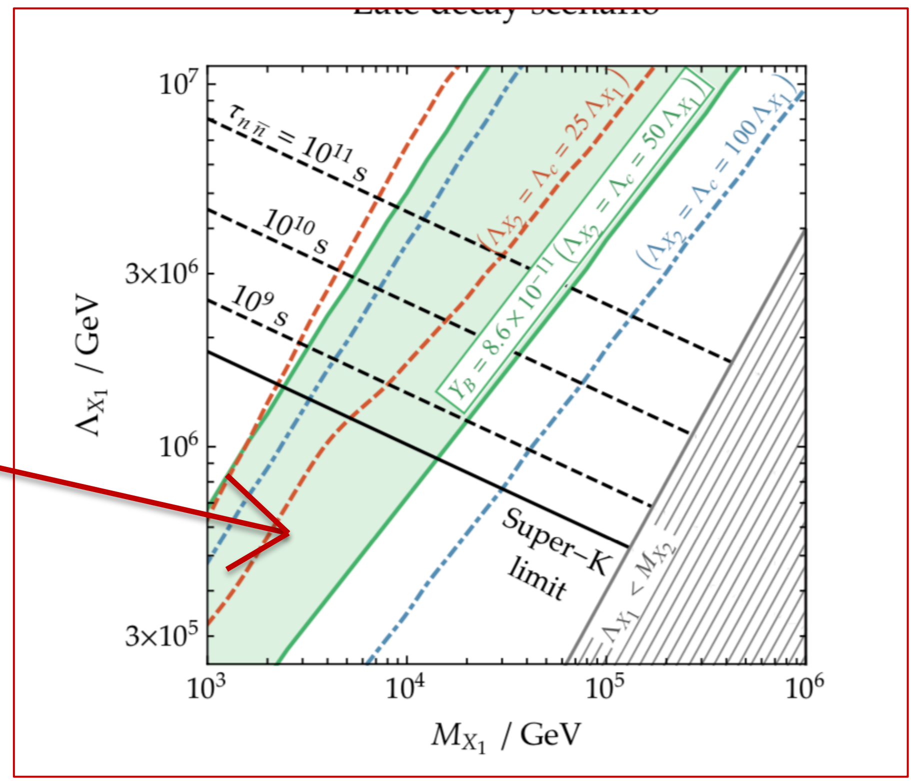
- Include both left and right handed quarks coupling to same sextet scalars, they enhance PSB→edm of neutron: (Bell, Musolf, Corbett, Nee'19)

Testing Majorana fermion mediated theory of NN-bar

- .Effective interaction: $\frac{1}{\Lambda^2}\chi u d d$
- NN-bar graph:



- Baryogenesis:



Grojean, Wells, Sakya,Zhang'18;

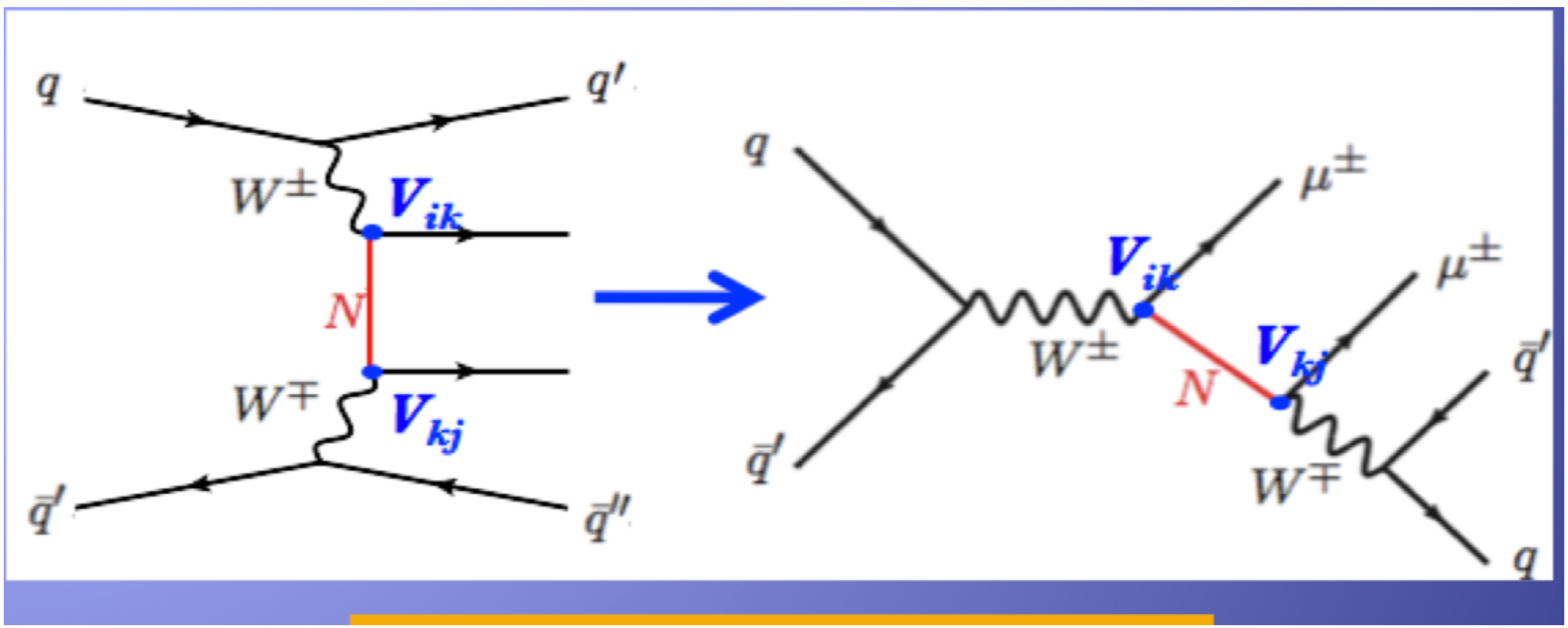
What else can NN-bar search teach us?

A fundamental question in particle physics now is whether neutrino is a Dirac or Majorana fermion?

Key evidences that will settle this issue are signals in searches for processes:

(i) $2n \rightarrow 2p + 2e^-$ (ii) $pp \rightarrow \ell^+ \ell^+ jj + X$

(iii) B-meson decays: e.g. $B \rightarrow K \ell^+ \ell^+$,..



Prospects for $\beta\beta_{0\nu}$

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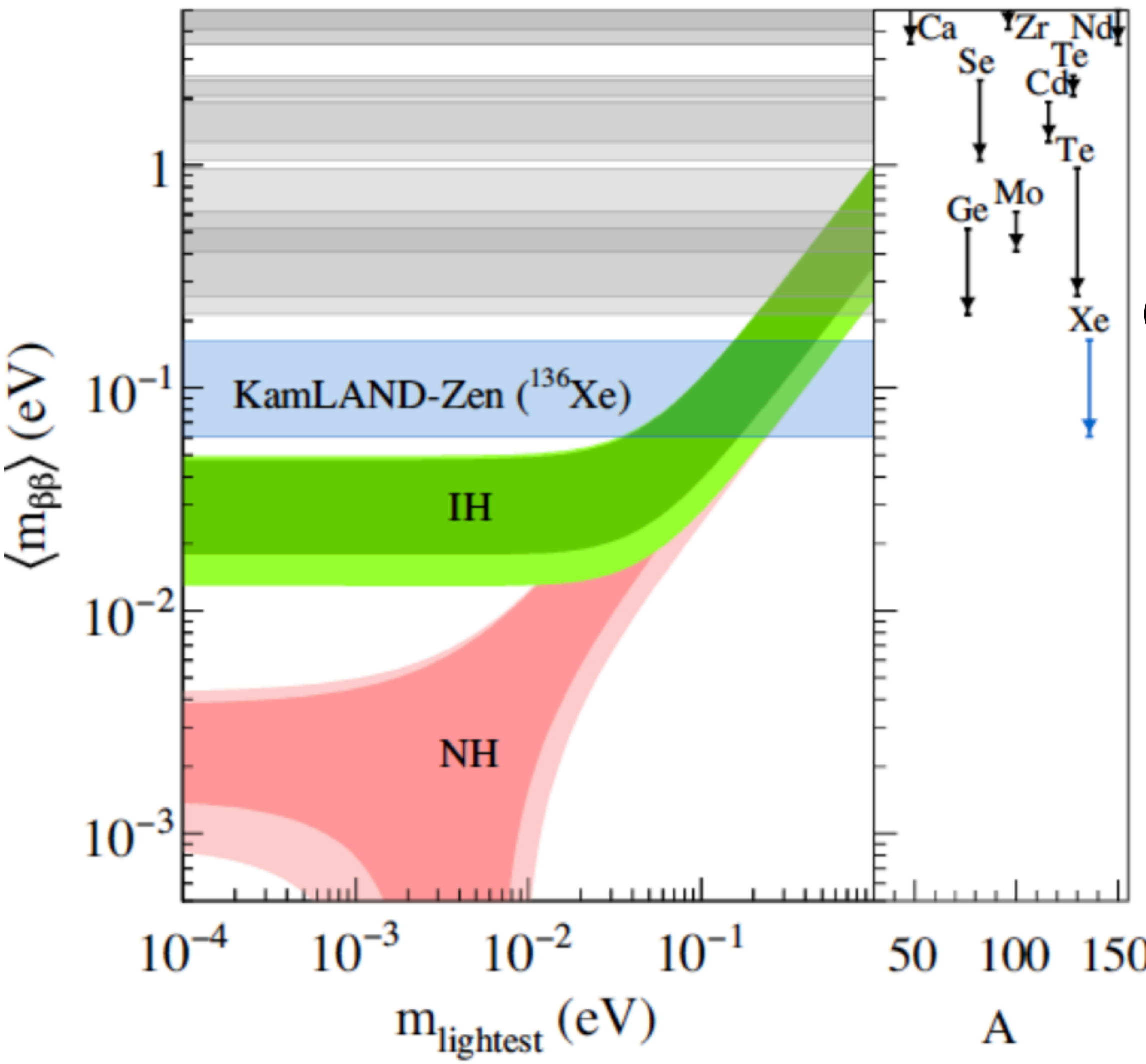


Hard for the case of NH.

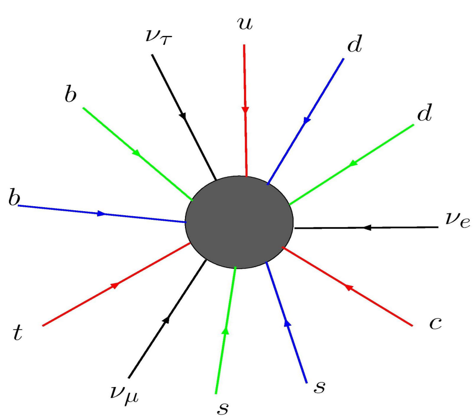
Is there another way to find out the true nature of the neutrino, should double beta decay searches turn fruitless?

We show that B-violation search, specifically nn-bar may provide another way!

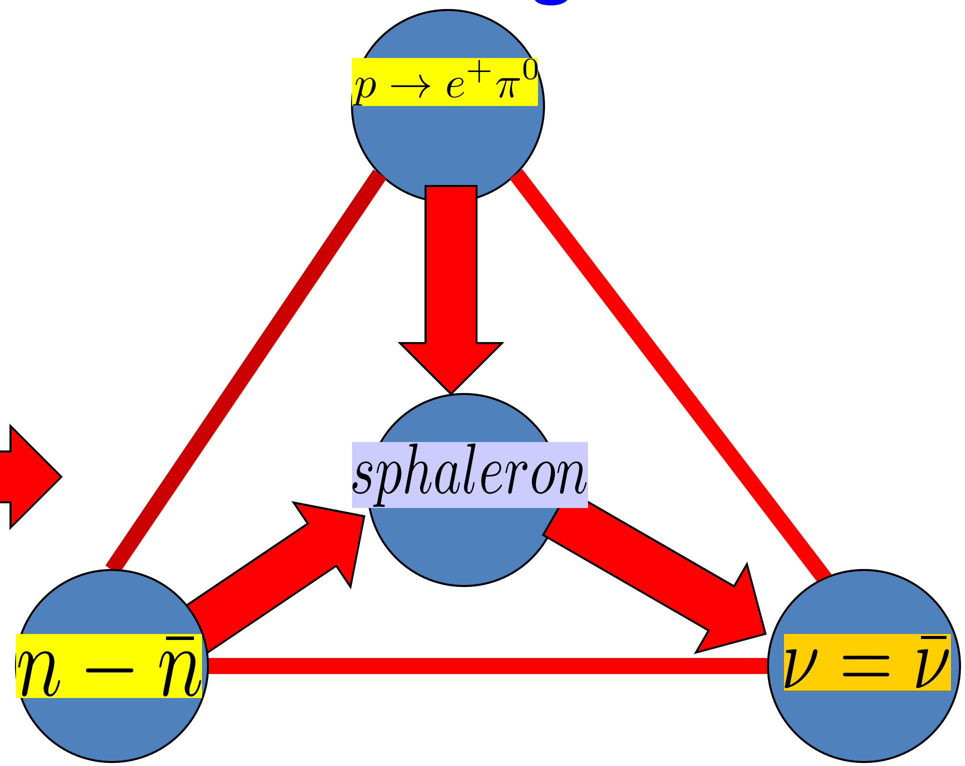
Sphalerons and B-L triangle

- Standard model has sphaleron solutions
- Sphaleron Op. rewrite

$$\underbrace{QQQQQQ}_{n-\bar{n}}\ \underbrace{QQQL}_{p\to e^+\pi^0}\ \underbrace{LL}_{m_\nu}$$



B-L Triangle:



- *p-decay+nn-bar →Neutrino Majorana* *(RNM, 2014 ESS at CERN)*

Is it more generic to BSM?

Many theories of B, L-violation have this property:

Babu, RNM'2014

- The various B and L-violating processes in BSM:
- $p \rightarrow e^+ \pi^0$ (B-L=0)
- $n \rightarrow e^- \pi^+$ (B-L=2)
- $n \rightarrow \bar{n}$ (B=2; L=0)
- $\nu\nu$ or $\beta\beta_{0\nu}$ (B=0; L=2)

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Many theories of B, L-violation have this property:

Babu, RNM'2014

❖ The various B and L-violating processes of interest:

❖ $p \to e^+ \pi^0$ (B-L=0)

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❖ $\nu\nu$ or $\beta\beta_{0\nu}$ (B=0; L=2)

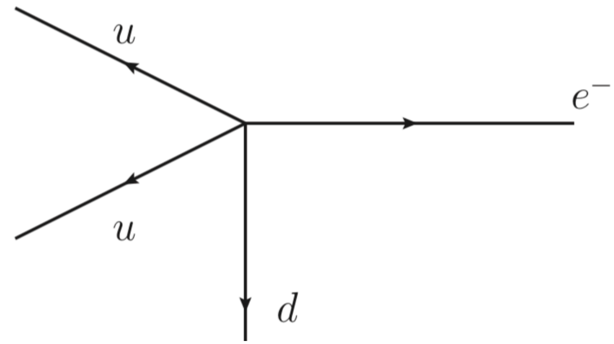
There are quite sensible theories (SO(10)) where they can coexist.

They have the triangular property i.e. two imply 3rd

Operator analysis of B-L triangle

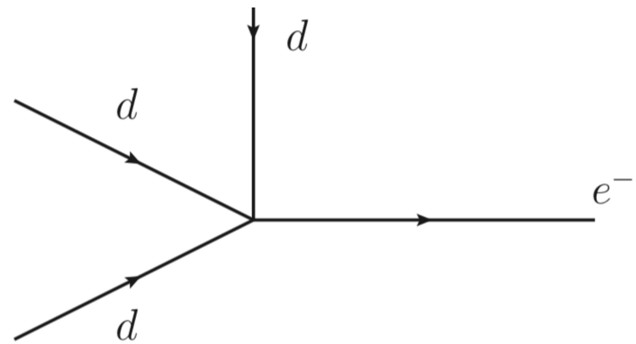
❖Typical operators for

- $p \to e^+ \pi^0$ → $uude^-$



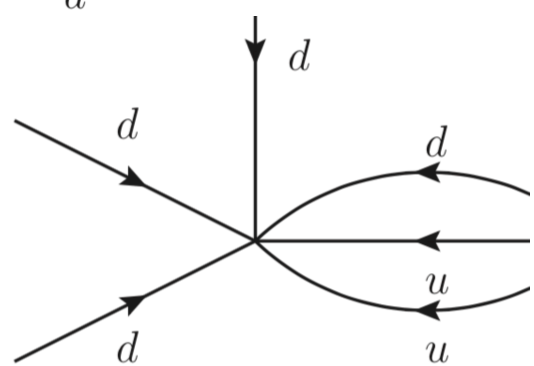
(B-L=0)

- $n \to e^- \pi^+$ → $ddde^+$



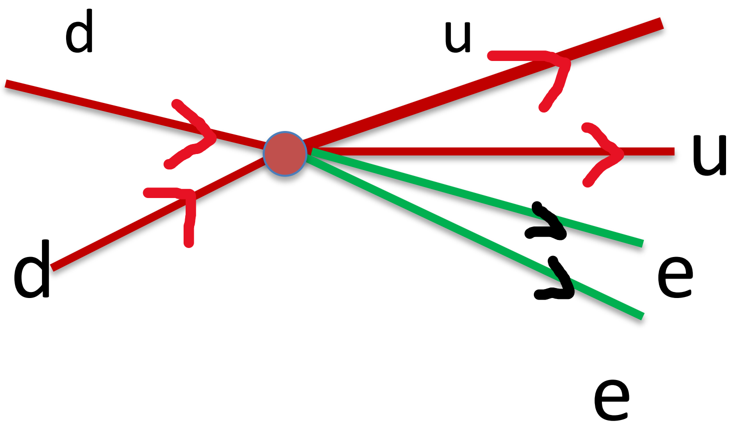
(B-L=2)

- $n \to \bar{n}$ → $uudddd$



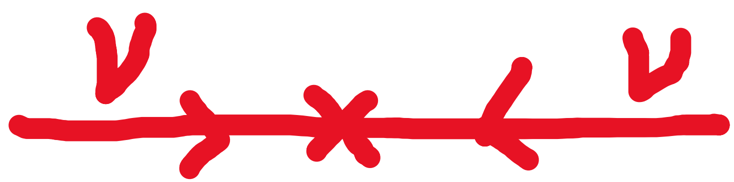
(B=2)

Operators for nu-less double beta decay and nu mass

- 

$$dd\bar{u}\bar{u}e^+e^+$$

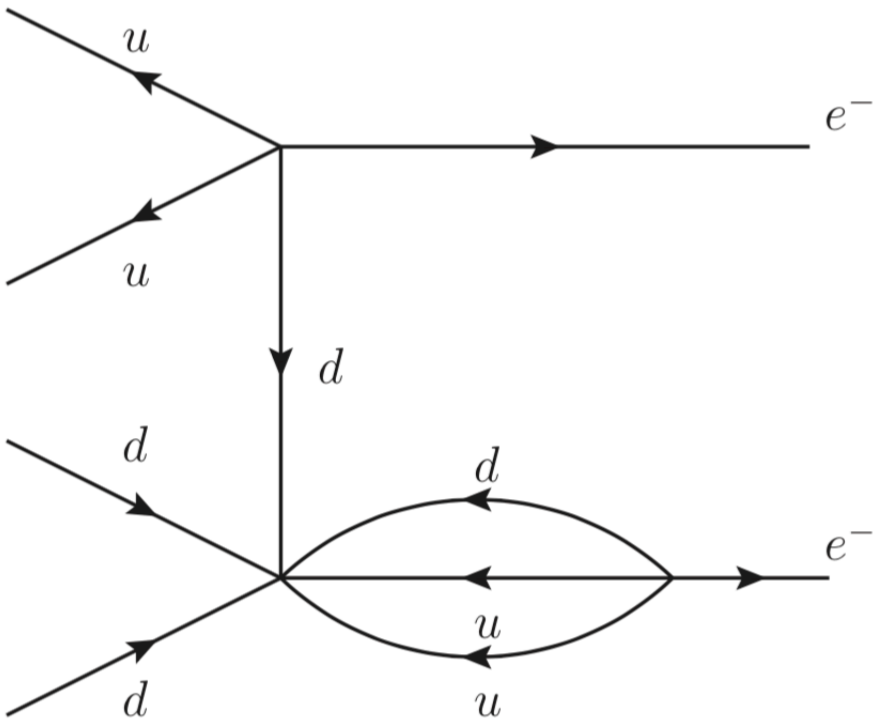
m_ν:



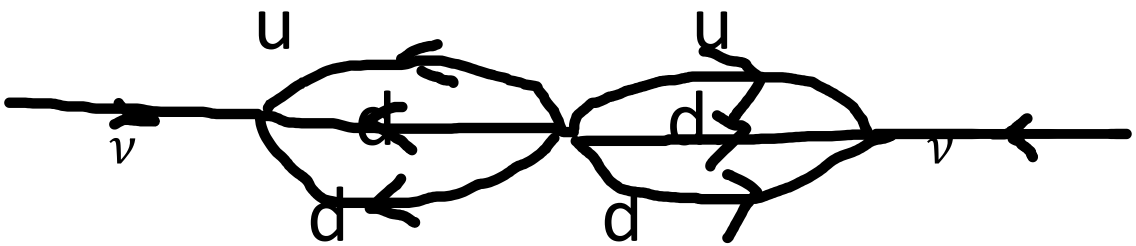
L=2

P-decay+ Nnbar→ΔL=2

- . $p \to e^+\pi^0$ + $n \to \bar{n}$ + $p \to e^+\pi^0$→$\beta\beta_{0\nu}$
- Diagramatically:



PROTON DECAYS + NN-BAR→ M_ν



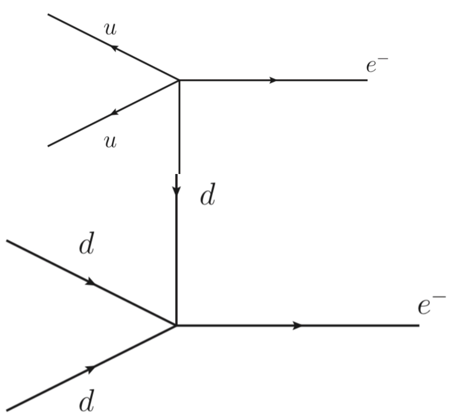
$$n \to \pi\bar{\nu} + n \to \pi\bar{\nu} + n\bar{n} = m_\nu$$

- All of these models lead to tiny nu masses but proves their Majorana nature!!

From nucleon decays to ΔL=2

- Combining the B=1 graphs, we can get graph for nu-less double beta decay i.e. L-violation by two units:
- $p \to e^+\pi^0$ + $n \to e^-\pi^+$ → nn→ppee ($\beta\beta_{0\nu}$)

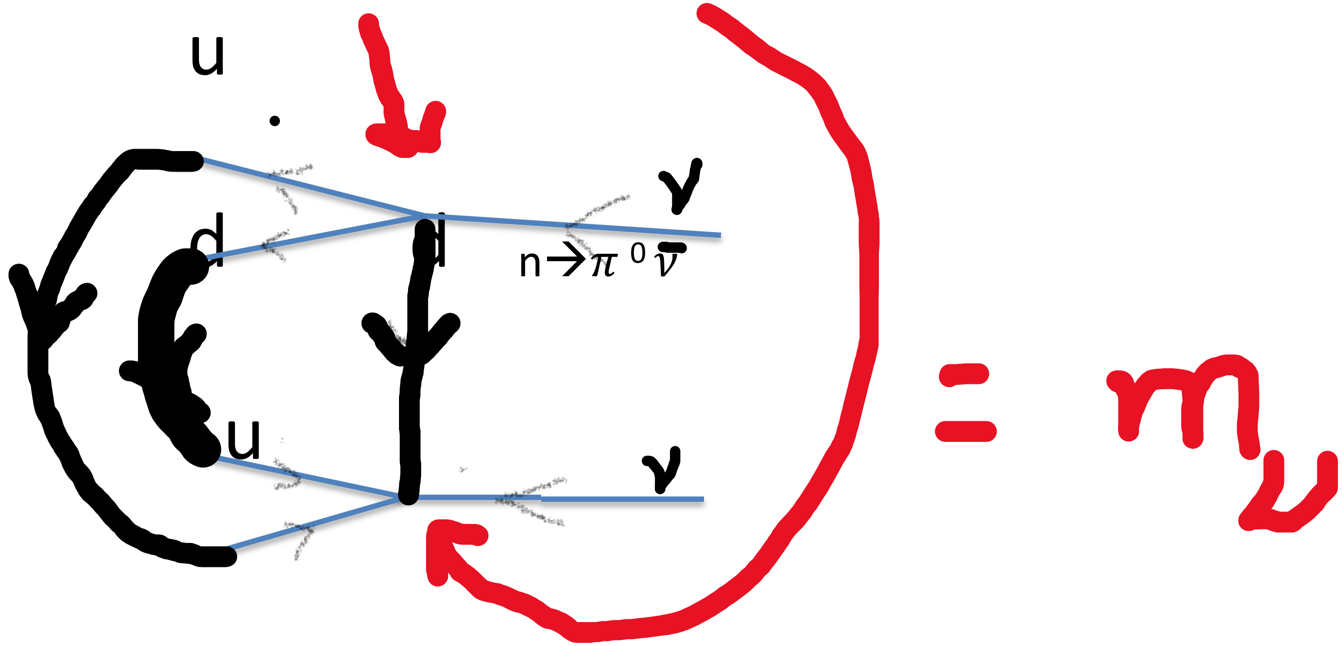
  B-L=0 B-L=2
- Operator for nu-less double beta decay: $dd\bar{u}\bar{u}e^+e^+$



$$dd\bar{u}\bar{u}e^+e^+$$

Direct generation of nu mass

- Combining B-L=2 and B-L=0 nucleon decay.



n→$\pi^0\bar{\nu}$

Comments on N-N’ oscillation

Mirror world & NN' oscillation

- If there is a parallel sector to our universe and if, the two sectors are identical, there can be neutron-mirror neutron oscillation (Berezhiani Bento'06; Berezhiani, Nesti'12)
- DM and possible nu_sterile could be hints for this.
- This model brings in other constraints:

visible sector	mirror sector
$SU(2)_L \times U(1)_{I_{3R}} \times U(1)_{B-L}$	$SU(2)_L \times U(1)_{I_{3R}} \times U(1)_{B-L}$
W, Z, γ, gluons	W, Z, γ, gluons
$\begin{pmatrix} u_L \\ d_L \end{pmatrix}$	$\begin{pmatrix} u_L \\ d_L \end{pmatrix}$
u_R, d_R	u_R, d_R
$\begin{pmatrix} \nu_L \\ e_L \end{pmatrix}$	$\begin{pmatrix} \nu_L \\ e_L \end{pmatrix}$
e_R	e_R
Higgs H_1, H_2, Δ_L	H_1, Δ_L

Cosmology And suppression of NN' oscillation

- BBN consistency requires N_{eff} =3.2 0r so. Implies that there must be asymmetric inflation in the early universe so that ν' and γ' do not contribute to BBN→

$$T_{RH}' < T_{RH}$$

(Berezhiani, Dolgov, Mohapatra'1995)

- This implies that at T=0, two sectors cannot be identical leading to $m_n \neq m_{n'}$. This can be quantified.
- This suppresses of NN' unless the picture of inflation is custom designed not to.
- So, observation of NN' will tell what this inflation picture is. Necessarily will lead to very low reheat Temperature. (RNM and Nussinov'18)

Are NN and NN' connected: A Model

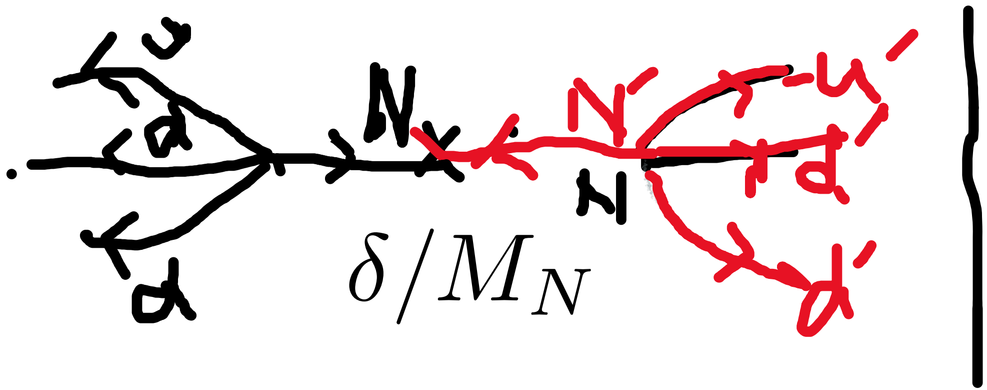
- Consider exact softly broken symmetric mirror model. $\delta\mathcal{L} = M_N(NN + \epsilon N'N') + \delta NN'$; $\epsilon \ll 1$
- Neutrino mass generated by one loop seesaw!
- N, N' RHNs connecting two sectors.
- $m_\nu \sim \frac{m^2_{eff}}{M_N}; m_{\nu'} \sim \frac{m^2_{eff}}{\epsilon M_N}; \sin\theta_{\nu\nu'} \simeq \frac{m_\nu}{m_{\nu'}}\frac{\delta}{\epsilon M_N}$
- Suppose nn' oscillation comes from:

$$\delta\mathcal{L}_{nn'} = \frac{1}{M^2}(Nudd + N'u'd'd')$$

RELATING NN TO NN' VIA STERILE NU

- Feynman graphs for n-n' and nn-bar oscillation

$G_{nn'/nn}$



δ/M_N

u

d

d

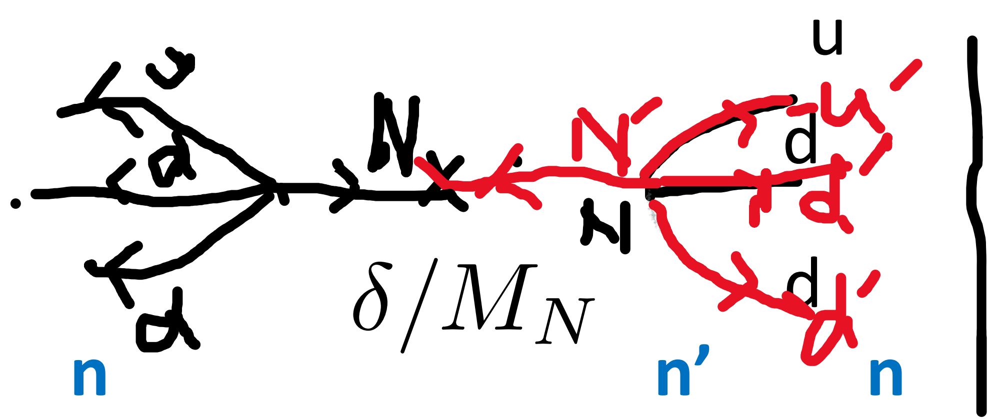
- n n' n

$$G_{nn'} = \frac{\delta}{M^4 \epsilon M_N^2} \qquad G_{nn} = \frac{1}{M^4 M_N}$$

Relating NN to NN' via sterile nu

- Feynman graphs for n-n' and nn-bar oscillation

$G_{nn'/nn}$



$$\boxed{\tau_{nn} \simeq \tau_{nn'} \frac{m'_\nu}{m_\nu} \sin\theta_{\nu\nu'}}$$

(In progress, Babu, RNM'20)

Implications of observable NN' for cosmology in this model

- Observable nn' → $M_{N,N'}$ must be ~10-100 TeV range
- → For T > M_N /5 TeV, mirror and visible sectors thermalize and BBN rules out such mirror models;
- Unless post-inflation reheating **T_{RH} < 2-20 TeV;** Low scale inflation needed.
- Baryogenesis then must be post-sphaleron type or TeV scale leptogenesis.

Binary pulsars and NN' oscillation rate

- NN' oscillation reduces mass of a pulsar because the n' does not feel the same nuclear force and drops to the center of the pulsar which increases its binding energy-(GMm/R)-> As BE increases, pulsar mass goes down;
- Mass loss $\propto \delta_{nn'}$
- Mass loss $\propto$ increase of binary pulsar period

$$\frac{dP_b/dt}{P_b} = -2\frac{dM/dt}{M}$$

- Observed limits on slow down rates→ $\delta < 10^{-22}$ GeV

$\tau > 0.01$ sec.

(Goldman, Nussinov, RNM'18)

Conclusion (I)

- Reasons to expect neutron oscillation are theoretically as compelling as proton decay
- Neutrino mass connection and direct connection to origin of matter prefer nn-bar over canonical GUT proton decay.
- If n-n bar is observed, GUT baryogenesis or leptogenesis do not work and origin of matter is most likely via post-sphaleron baryogenesis, testable in ESS nnbar search

Conclusion(II)

- If neutrino-less double beta decay experiments do not show any +ve signal, how do we answer the fundamental question of whether neutrinos are Dirac or Majorana?
- One way: if proton decay and nnbar together are observed, they would imply that nus are Majorana. Proton decay searches are on. Very important to search for nn-bar osc.

Conclusion(III)

- If there is a sterile nu, nn-bar and nn’ rates can be related. This relation can be tested.
- In which case, the inflation must lead to low scale reheating.
- Different from the conventional inflation scenarios!

Thank you for your attention !!

What kind of $\beta\beta_{0\upsilon}$ life times expected?

$$A_{\beta\beta_0\nu} \sim A_{p\to e^+\pi^0} A_{n\to e^-\pi^+}/m_u$$

- → $\tau_{\beta\beta} > 10^{112}$ yrs
- → $m_\nu \leq 10^{-44}\mathrm{eV}$ (Majorana mass)
- There necessarily are other contributions to nu mass!!

Recent review of phenomenology and experimental prospects

NNBar Experiment at the ESS

New high-sensitivity searches for neutrons converting into antineutrons and/or sterile neutrons at the European Spallation Source

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Preprint submitted to Elsevier *June 11, 2020*

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Direct generation of nu mass

- Combining B-L=2 and B-L=0 nucleon decay