A ν Leaf: How to Search for Majorana Dynamics at Low-Energy Accelerators

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Fundamental Majorana Dynamics

Can exist for electrically neutral massive fermions: either leptons (ν's) or combinations of quarks (n's)

Lorentz invariance allows

$$\mathcal{L} = \bar{\psi} i \partial\!\!\!/ \psi - \frac{1}{2} m (\psi^T C \psi + \bar{\psi} C \bar{\psi}^T)$$

[Majorana, 1937]

where m is the Majorana mass.

N.B. a "Majorana neutron" is an entangled n and $\bar{n}$ state

Bibliography:
S.G. & Xinshuai Yan (U. Kentucky), Phys. Rev. D93, 096008 (2016) [arXiv:1602.00693];
S.G. & Xinshuai Yan, Phys. Rev. D97, 056008 (2018) [arXiv:1710.09292];
S.G. & Xinshuai Yan, Phys. Lett. B790 (2019) 421 [arXiv:1808.05288];
and on ongoing work in collaboration with Xinshuai Yan

Why Search for n-$\bar{n}$ Oscillations?

The Standard Model (SM) cannot explain the origin of the cosmic BAU, dark matter, or dark energy.

B violation plays a role in at least one of these puzzles.

Although B violation appears in the SM (sphalerons),

[Kuzmin, Rubakov, & Shaposhnikov, 1985]

we know nothing of its pattern at accessible energies.

Do processes occur with $|\Delta B|=1$ or $|\Delta B|=2$ or both?

The SM conserves B-L, but does Nature?

Despite severe limits on $|\Delta B|=1$ processes, the origin of $|\Delta B|=2$ processes can be completely distinct

[Marshak and Mohapatra, 1980; Babu & Mohapatra, 2001 & 2012; Arnold, Fornal, & Wise, 2013]

If neutron-antineutron oscillations, e.g., are observed, then B-L is broken, and we have found physics BSM!

On Neutrinoless Double Beta ($0\nu\ \beta\beta$) decay

If observed, the ν has a Majorana mass

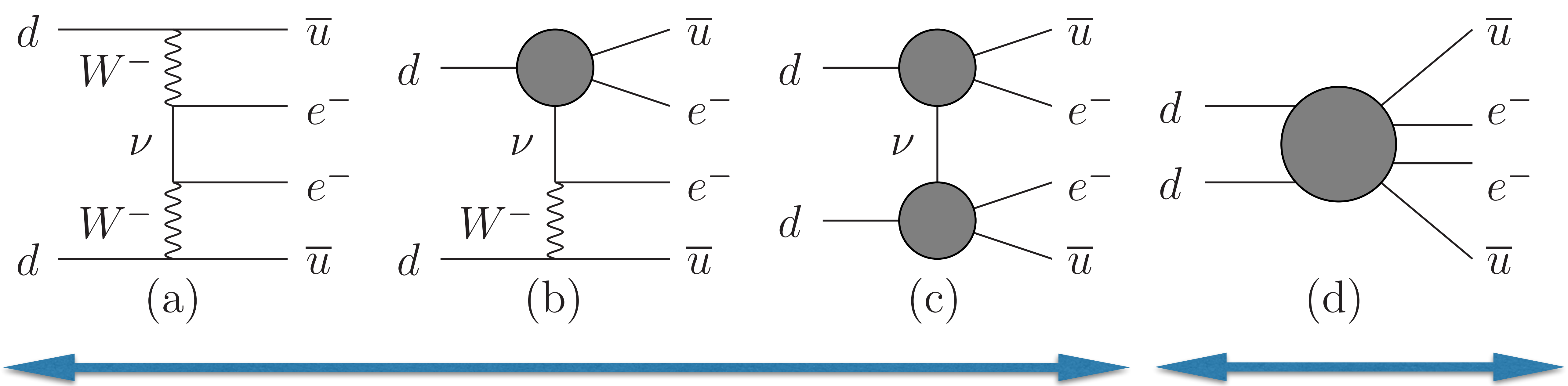
[Schechter & Valle, 1982]

$0\nu\ \beta\beta$ mediated by a dimension 9 operator:

$$\mathcal{O} \propto \bar{u}\bar{u}dd\bar{e}\bar{e}$$

(or $\pi^- \pi^- \rightarrow e^- e^-$)

"mass mechanism"



"long range"

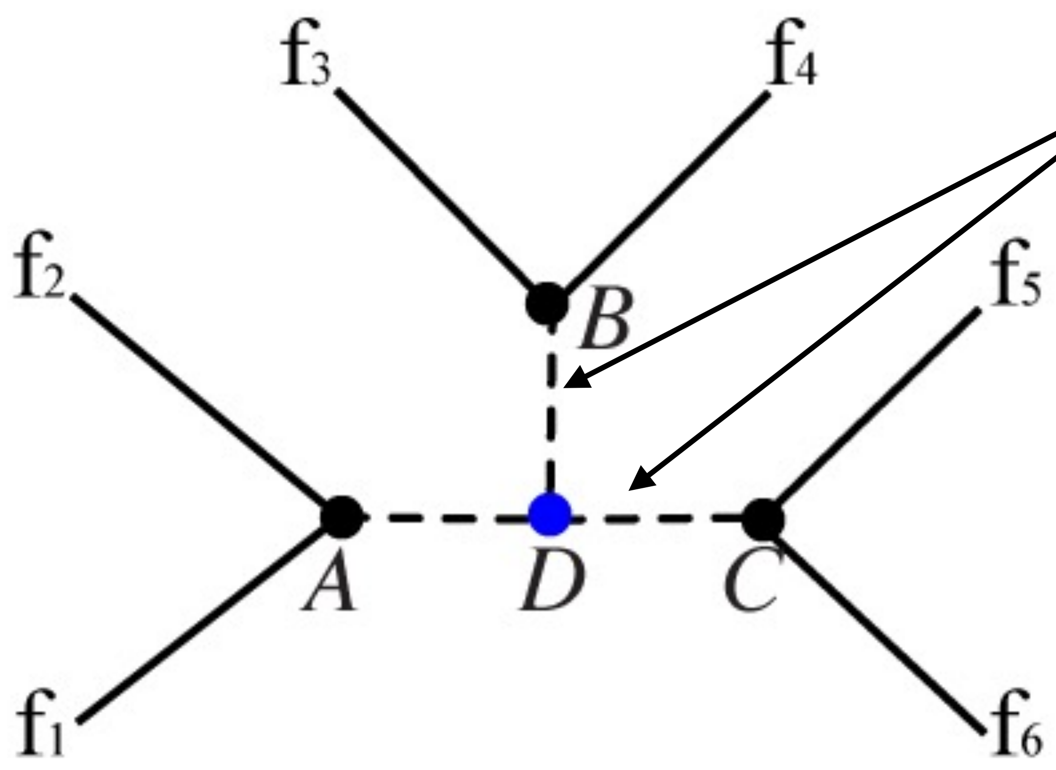
"short range"

[Bonnet, Hirsch, Ota, & Winter, 2013]

0ν ββ Decay in Nuclei

Can be mediated by "short-" or "long"-range mechanisms

The "short-range" mechanism involves new B-L violating dynamics; e.g.,



S or V that carries B or L

For choices of fermions f_i this decay topology can yield n-$\bar{n}$ or 0ν ββ decay

[Bonnet, Hirsch, Ota, & Winter, 2013]

Can we relate the possibilities in a data-driven way?

[Yes!] [S.G. & Xinshuai Yan, 2019]

Cf. connection via |ΔB|=1 process
[Babu & Mohapatra, 2015]

Nucleon-Antinucleon Transitions

Can be realized in different ways

Enter searches for

- neutron-antineutron oscillations (free n's & in nuclei)

"spontaneous"
& thus sensitive to
environment

$$\mathcal{M} = \begin{pmatrix} M_n - \mu_n B & \delta \\ \delta & M_n + \mu_n B \end{pmatrix}$$

$$P_{n\to\bar{n}}(t) \simeq \frac{\delta^2}{2(\mu_n B)^2}\left[1 - \cos(2\mu_n B t)\right]$$

- dinucleon decay (in nuclei)
  (limited by finite nuclear density)
- nucleon-antinucleon conversion (NEW!)
  (mediated by external interactions) [SG & Xinshuai Yan]

Effective Lagrangian

Neutron interactions with B-L violation & electromagnetism

$$\mathcal{L}_{\rm eff} \supset -\frac{1}{2}\mu_n \bar{n}\sigma^{\mu\nu} n F_{\mu\nu} - \frac{\delta}{2} n^T C n - \frac{\eta}{2} n^T C \gamma^\mu \gamma^5 n j_\mu + \text{h.c.}$$

$$[\, Qej^\nu = \partial_\mu F^{\mu\nu} \,]$$

magnetic moment

$n \to \bar{n}$ oscillation

"spontaneous" → oscillation

$n \to \bar{n}$ conversion

[SG & Xinshuai Yan, arXiv: 1710.09292]

Since the quarks carry electric charge, a BSM model that generates neutron-antineutron oscillations can also generate conversion

Neutron-Antineutron Conversion

Different mechanisms are possible

* n-$\bar{n}$ conversion and oscillation could share the same "TeV" scale BSM sources
  → Then the quark-level conversion operators can be derived noting the quarks carry electric charge

* n-$\bar{n}$ conversion and oscillation could come from different BSM sources

  → Indeed different $|\Delta B|=2$ processes could appear (e.g., $e^- p \to e^+ \bar{p}$)

$N\bar{N}$ conversion

Neutron-Antineutron Oscillation

Quark-level operators

[Rao & Shrock, 1982]

$$(\mathcal{O}_1)_{\chi_1\chi_2\chi_3} = [u^{T\alpha}_{\chi_1} C u^{\beta}_{\chi_1}][d^{T\gamma}_{\chi_2} C d^{\delta}_{\chi_2}][d^{T\rho}_{\chi_3} C d^{\sigma}_{\chi_3}](T_s)_{\alpha\beta\gamma\delta\rho\sigma},$$

$$(\mathcal{O}_2)_{\chi_1\chi_2\chi_3} = [u^{T\alpha}_{\chi_1} C d^{\beta}_{\chi_1}][u^{T\gamma}_{\chi_2} C d^{\delta}_{\chi_2}][d^{T\rho}_{\chi_3} C d^{\sigma}_{\chi_3}](T_s)_{\alpha\beta\gamma\delta\rho\sigma},$$

$$(T_s)_{\alpha\beta\gamma\delta\rho\sigma} = \epsilon_{\rho\alpha\gamma}\epsilon_{\sigma\beta\delta} + \epsilon_{\sigma\alpha\gamma}\epsilon_{\rho\beta\delta} + \epsilon_{\rho\beta\gamma}\epsilon_{\sigma\alpha\delta} + \epsilon_{\sigma\beta\gamma}\epsilon_{\rho\alpha\delta},$$

Note

$O_2 \rightarrow O_3$

$T_s \rightarrow T_a$

$$(T_a)_{\alpha\beta\gamma\delta\rho\sigma} = \epsilon_{\rho\alpha\beta}\epsilon_{\sigma\gamma\delta} + \epsilon_{\sigma\alpha\beta}\epsilon_{\rho\gamma\delta}$$

- Only 14 of 24 operators are independent

$$(\mathcal{O}_1)_{\chi_1 LR} = (\mathcal{O}_1)_{\chi_1 RL}, \qquad (\mathcal{O}_{2,3})_{LR\chi_3} = (\mathcal{O}_{2,3})_{RL\chi_3},$$

$$(\mathcal{O}_2)_{mmn} - (\mathcal{O}_1)_{mmn} = 3(\mathcal{O}_3)_{mmn}$$ [Caswell, Milutinovic, & Senjanovic, 1983]

- Only 4 appear in SM effective theory

[Rao & Shrock, 1982]

From Oscillation to Conversion

Quark-level operators: compute $q^\rho(p)+\gamma(k)\to\bar{q}^\delta(p')$

flavor

$$\mathcal{H}_I \supset \frac{\delta_q}{2}\sum_{\chi_1}(\psi^{\rho T}_{\chi_1} C\psi^\delta_{\chi_1} + \bar\psi^\delta_{\chi_1} C\bar\psi^{\rho T}_{\chi_1}) + Q_\rho e\sum_{\chi_2}\bar\psi^\rho_{\chi_2}\not{A}\psi^\rho_{\chi_2}$$
$$+ Q_\delta e\sum_{\chi_3}\bar\psi^\delta_{\chi_3}\not{A}\psi^\delta_{\chi_3},$$

chiral basis

matrix element:

$$\langle\bar q^\delta(p')|\mathcal{T}\left(\sum_{\chi_1,\chi_2}\left(-i\frac{\delta_q}{2}\int d^4x\psi^{\rho T}_{\chi_1}C\psi^\delta_{\chi_1}\right)\right.$$
$$\left.\times\left(-iQ_\rho e\int d^4y\bar\psi^\rho_{\chi_2}\not{A}\psi^\rho_{\chi_2} - iQ_\delta e\int d^4y\bar\psi^\delta_{\chi_2}\not{A}\psi^\delta_{\chi_2}\right)\right)$$
$$\times|q^\rho(p)\gamma(k)\rangle,$$

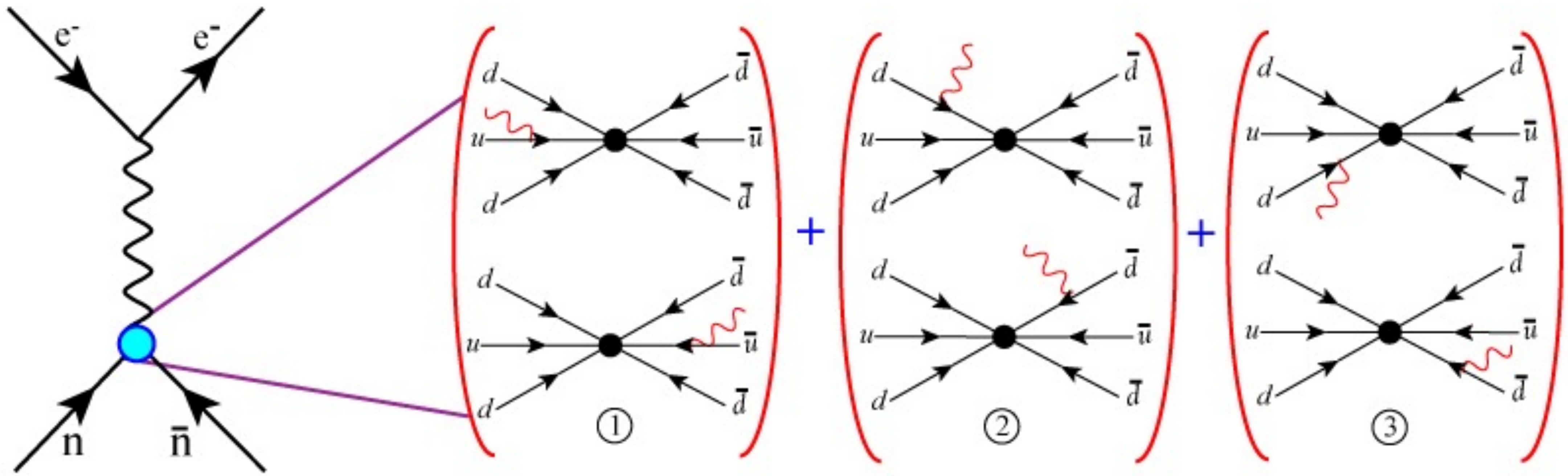
- if $\delta=\rho$ yields $C\gamma_\mu\gamma_5$ only

Effective vertex

$$-\frac{m\delta_q e}{p^2-m^2}(Q_\rho\psi^{\delta T}_{-\chi_2}C\gamma^\mu\psi^\rho_{\chi_2} - Q_\delta\psi^{\delta T}_{\chi_2}C\gamma^\mu\psi^\rho_{-\chi_2}),$$

B-L Violation via e-n scattering

Linking neutron-antineutron oscillation to conversion



e.g.:

$$(\mathcal{O}_2)_{\chi_1\chi_2\chi_3} = [u^{T\alpha}_{\chi_1} C d^{\beta}_{\chi_1}][u^{T\gamma}_{\chi_2} C d^{\delta}_{\chi_2}][d^{T\rho}_{\chi_3} C d^{\sigma}_{\chi_3}](T_s)_{\alpha\beta\gamma\delta\rho\sigma}$$

[Rao & Shrock, 1982]

$$(\tilde{\mathcal{O}}_2)^{\chi\,\mu}_{\chi_1\chi_2\chi_3} = \Big[[u^{\alpha\,T}_{-\chi} C\gamma^\mu\gamma_5 d^\beta_\chi - 2u^{\alpha\,T}_{\chi} C\gamma^\mu\gamma_5 d^\beta_{-\chi}][u^{\gamma\,T}_{\chi_2} C d^\delta_{\chi_2}][d^{\rho\,T}_{\chi_3} C d^\sigma_{\chi_3}]$$

$$+[u^{\alpha\,T}_{\chi_1} C d^\beta_{\chi_1}][u^{\gamma\,T}_{-\chi} C\gamma^\mu\gamma_5 d^\delta_\chi - 2u^{\gamma\,T}_{\chi} C\gamma^\mu\gamma_5 d^\delta_{-\chi}][d^{\rho\,T}_{\chi_3} C d^\sigma_{\chi_3}]$$

$$+[u^{\alpha\,T}_{\chi_1} C d^\beta_{\chi_1}][u^{\gamma\,T}_{\chi_2} C d^\delta_{\chi_2}][d^{\rho\,T}_{-\chi} C\gamma^\mu\gamma_5 d^\sigma_\chi + d^{\rho\,T}_{\chi} C\gamma^\mu\gamma_5 d^\sigma_{-\chi}]\Big] \mathrm{T_s}\ldots$$

B-L Violation via e-n scattering

Linking neutron-antineutron oscillation to conversion

Moreover...

$$
\begin{aligned}
(\tilde{\mathcal{O}}_1)^{\chi\,\mu}_{\chi_1\chi_2\chi_3} = & \Big[-2[u^{\alpha\,T}_{-\chi} C\gamma^\mu\gamma_5 u^\beta_\chi + u^{\alpha\,T}_{\chi} C\gamma^\mu\gamma_5 u^\beta_{-\chi}][d^{\gamma\,T}_{\chi_2} C d^\delta_{\chi_2}][d^{\rho\,T}_{\chi_3} C d^\sigma_{\chi_3}] \\
+ & [u^{\alpha\,T}_{\chi_1} C u^\beta_{\chi_1}][d^{\gamma\,T}_{-\chi} C\gamma^\mu\gamma_5 d^\delta_\chi + d^{\gamma\,T}_{\chi} C\gamma^\mu\gamma_5 d^\delta_{-\chi}][d^{\rho\,T}_{\chi_3} C d^\sigma_{\chi_3}] \\
+ & [u^{\alpha\,T}_{\chi_1} C u^\beta_{\chi_1}][d^{\gamma\,T}_{\chi_2} C d^\delta_{\chi_2}][d^{\rho\,T}_{-\chi} C\gamma^\mu\gamma_5 d^\sigma_\chi + d^{\rho\,T}_{\chi} C\gamma^\mu\gamma_5 d^\sigma_{-\chi}] \Big] (T_s)_{\alpha\beta\gamma\delta\rho\sigma}
\end{aligned}
$$

yielding [Here χ=R - χ=L for em scattering]

$$
(\tilde{\mathcal{O}}_1)^{\chi}_{\chi_1\chi_2\chi_3} = (\delta_1)_{\chi_1\chi_2\chi_3} \frac{em}{3(p^2_{\rm eff} - m^2)} \frac{Qej_\mu}{q^2} (\tilde{\mathcal{O}}_1)^{\chi\,\mu}_{\chi_1\chi_2\chi_3} \,,
$$

(best connection to oscillation as $q^2 \to 0$)

with similar relationships for i=2,3 [only these in em case]

The hadronic matrix elements are computed in the MIT bag model.

B-L Violation via e-n scattering

Linking neutron-antineutron oscillation to conversion

[SG & Xinshuai Yan, arXiv:1710.09292, PRD 2018]

TABLE I. Dimensionless matrix elements $(I_i)^{\chi 3}_{\chi_1 \chi_2 \chi_3}$ of $n - \bar{n}$ conversion operators. The column "EM" denotes the matrix-element combination of $(\chi = \mathrm{R}) - (\chi = \mathrm{L})$.

	I_1				I_2				I_3		
$\chi_1\chi_2\chi_3$	$\chi = R$	$\chi = L$	EM	$\chi_1\chi_2\chi_3$	$\chi = R$	$\chi = L$	EM	$\chi_1\chi_2\chi_3$	$\chi = R$	$\chi = L$	EM
RRR	19.8	19.8	0	RRR	-4.95	-4.95	0	RRR	1.80	-8.28	10.1
RRL	17.3	17.3	0	RRL	-2.00	-9.02	7.02	RRL	-1.07	-8.81	7.74
RLR	17.3	17.3	0	RLR	-4.09	-0.586	-3.50	RLR	7.20	6.03	1.17
RLL	6.02	6.02	0	RLL	-0.586	-4.09	3.50	RLL	6.03	7.20	-1.17
LRR	6.02	6.02	0	LRR	-4.09	-0.586	-3.50	LRR	7.20	6.03	1.17
LRL	17.3	17.3	0	LRL	-0.586	-4.09	3.50	LRL	6.03	7.20	-1.17
LLR	17.3	17.3	0	LLR	-9.02	-2.00	-7.02	LLR	-8.81	-1.07	-7.74
LLL	19.8	19.8	0	LLL	-4.95	-4.95	0	LLL	-8.28	1.80	-10.1

Electromagnetic scattering yields n-n̄ conversion from O_2 and O_3 operators only!

Interactions impact view on n-n̄ osc. even in $q^2 \rightarrow 0$ limit; (cf. K_S regeneration in matter); cf. Nesvizhevsky et al 2018….

Neutron-Antineutron Conversion

Different mechanisms are possible

* n-$\bar{n}$ conversion and oscillation could share the same "TeV" scale BSM sources
  → Then the quark-level conversion operators can be derived noting the quarks carry electric charge

* n-$\bar{n}$ conversion and oscillation could come from different BSM sources
  ★ → Here we consider nucleon-antinucleon conversion

Now we turn to minimal scalar models.

Models with |ΔB|=2 Processes

Enter minimal scalar models without proton decay

[Arnold, Fornal, and Wise, 2013; Dev & Mohapatra, 2015]

Already used for $n \to \bar{n}$ oscillation without p decay

[Arnold, Fornal, Wise, PRD, 2013]

Note limits on |ΔB|=1 processes are severe!

E.g., $\tau(N \to e^+\pi) = 8.2 \times 10^{33}$ yr [p] @ 90% CL

Add new scalars X_i that do not give N decay at tree level

Also choose X_i that respect SM gauge symmetry and also under interactions $X_iX_jX_k$ or $X_iX_jX_kX_l$ — cf. "hidden sector" searches: possible masses are limited by experiment

Scalars without Proton Decay

That also carry B or L charge

TABLE I. Scalar particle representations in the $SU(3)_c \times SU(2)_L \times U(1)_Y$ SM that carry nonzero B and/or L but permit no proton decay at tree level, after Ref. [4]. We indicate the possible interactions between the scalar X and SM fermions schematically. Note that the indices a, b run over three generations, that the symmetry of the associated coupling g_i^{ab} under $a \leftrightarrow b$ exchange is noted in brackets, and finally that our convention for Y is $Q_{\rm em} = T_3 + Y$. Please refer to the text for further discussion.

Scalar	SM Representation	B	L	Operator(s)	$[g_i^{ab}?]$
X_1	$(1,1,2)$	0	-2	$Xe^a e^b$	[S]
X_2	$(1,1,1)$	0	-2	$XL^a L^b$	[A]
X_3	$(1,3,1)$	0	-2	$XL^a L^b$	[S]
X_4	$(\bar{6},3,-1/3)$	-2/3	0	$XQ^a Q^b$	[S]
X_5	$(\bar{6},1,-1/3)$	-2/3	0	$XQ^a Q^b, Xu^a d^b$	[A,–]
X_6	$(3,1,2/3)$	-2/3	0	$Xd^a d^b$	[A]
X_7	$(\bar{6},1,2/3)$	-2/3	0	$Xd^a d^b$	[S]
X_8	$(\bar{6},1,-4/3)$	-2/3	0	$Xu^a u^b$	[S]
X_9	$(3,2,7/6)$	1/3	-1	$X\bar{Q}^a e^b, XL^a \bar{u}^b$	[–,–]

Note SU(3) rep'ns

Scalar-fermion couplings

Patterns of |ΔB|=2 Violation?

Note possible SM gauge invariant scalar models

[SG & Xinshuai Yan, arXiv: 1808.05288]

TABLE II. Minimal interactions that break B and/or L from scalars X_i that do not permit $|\Delta B| = 1$ interactions at tree level, indicated schematically, with the Hermitian conjugate implied. Interactions labelled M1-M9 appear in models 1-9 of Ref. [4]. Interactions A-G possess $|\Delta L| = 2$, $|\Delta B| = 0$. M19, M20, and M21 follow from M8, M17, and M18 under $X_7 \to X_6$, respectively, but they do not involve first-generation fermions only.

Model		Model		Model	
M1	$X_5X_5X_7$	A	$X_1X_8X_7^\dagger$	M10	$X_7X_8X_8X_1$
M2	$X_4X_4X_7$	B	$X_3X_4X_7^\dagger$	M11	$X_5X_5X_4X_3$
M3	$X_7X_7X_8$	C	$X_3X_8X_4^\dagger$	M12	$X_5X_5X_8X_1$
M4	$X_6X_6X_8$	D	$X_5X_2X_7^\dagger$	M13	$X_4X_4X_5X_2$
M5	$X_5X_5X_5X_2$	E	$X_8X_2X_5^\dagger$	M14	$X_4X_4X_5X_3$
M6	$X_4X_4X_4X_2$	F	$X_2X_2X_1^\dagger$	M15	$X_4X_4X_8X_1$
M7	$X_4X_4X_4X_3$	G	$X_3X_3X_1^\dagger$	M16	$X_4X_7X_8X_3$
M8	$X_7X_7X_7X_1^\dagger$			M17	$X_5X_7X_7X_2^\dagger$
M9	$X_6X_6X_6X_1^\dagger$			M18	$X_4X_7X_7X_3^\dagger$

n-$\bar{n}$ (M1–M3)

$\pi^-\pi^- \to e^-e^-$ (A–C)

"4 X" models can yield

$e^- p \to e^+ \bar{p}$

$e^- p \to \bar{\nu}\, \bar{n}$

Patterns of |ΔB|=2 Violation?

Note possible BNV processes

[SG & Xinshuai Yan, arXiv: 1808.05288]

TABLE III. Suite of |ΔB| = 2 and |ΔL| = 2 processes generated by the models of Table II, focusing on states with first-generation matter. The (∗) superscript indicates that a weak isospin triplet of |ΔL| = 2 processes can appear, namely $\pi^0\pi^0 \to \nu\nu$ and $\pi^-\pi^0 \to e^-\nu$. Models M7, M11, M14, and M16 also support $\nu n \to \bar{n}\bar{\nu}$, revealing that cosmic ray neutrinos could potentially mediate a |ΔB| = 2 effect.

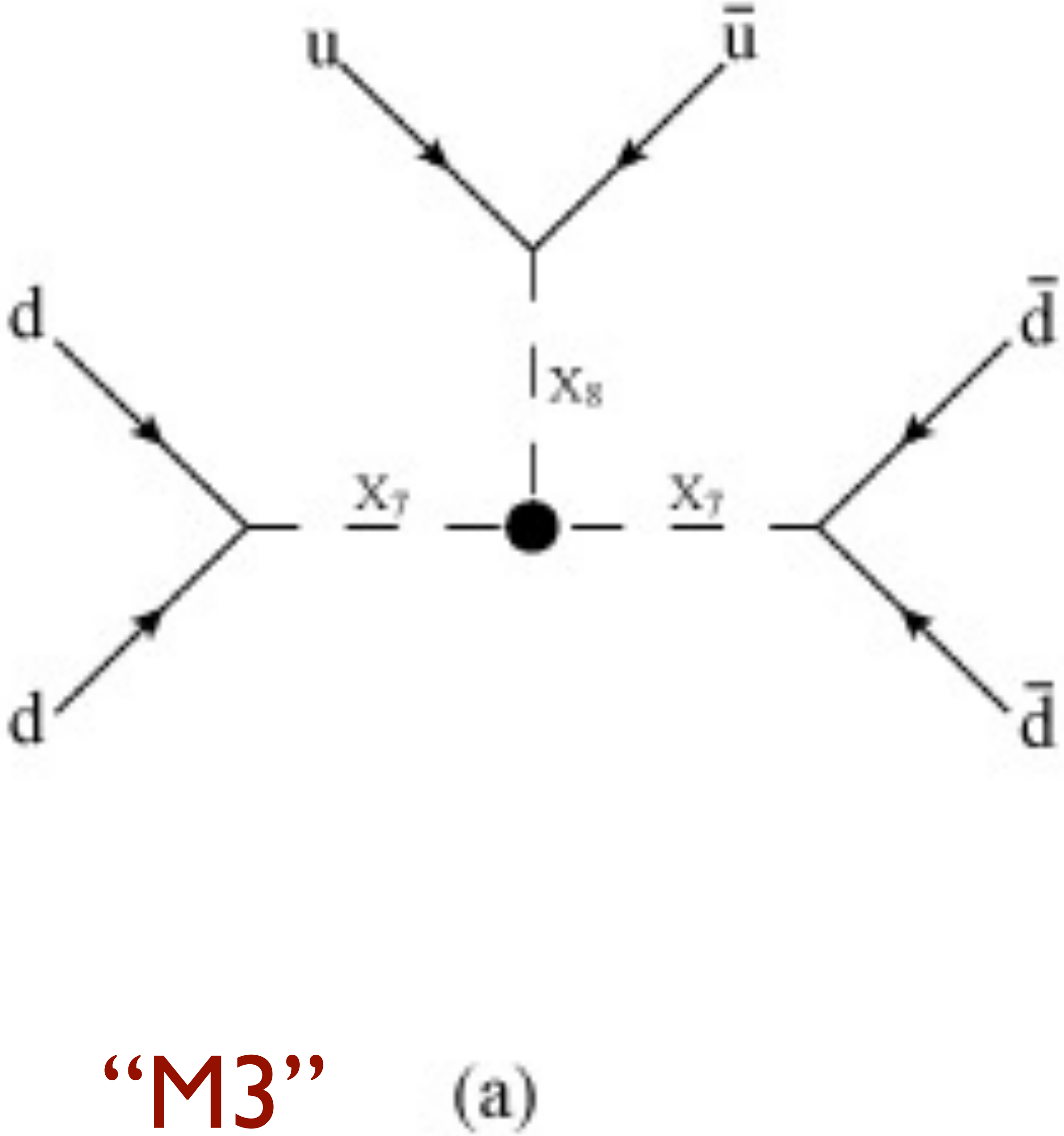
$n\bar{n}$	$\pi^-\pi^- \to e^-e^-$	$e^-p \to \bar{\nu}_{\mu,\tau}\bar{n}$	$e^-p \to \bar{\nu}_e\bar{n}/e^+\bar{p}$	$e^-p \to e^+\bar{p}$
M1	A	M5	M7	M10
M2	$B^{(*)}$	M6	M11	M12
M3	$C^{(*)}$	M13	M14	M15
			M16	

Use observations of $n\bar{n}$ oscillation or $N\bar{N}$ conversion ($e^- p \to e^+\bar{p}$, …) to establish new scalars…

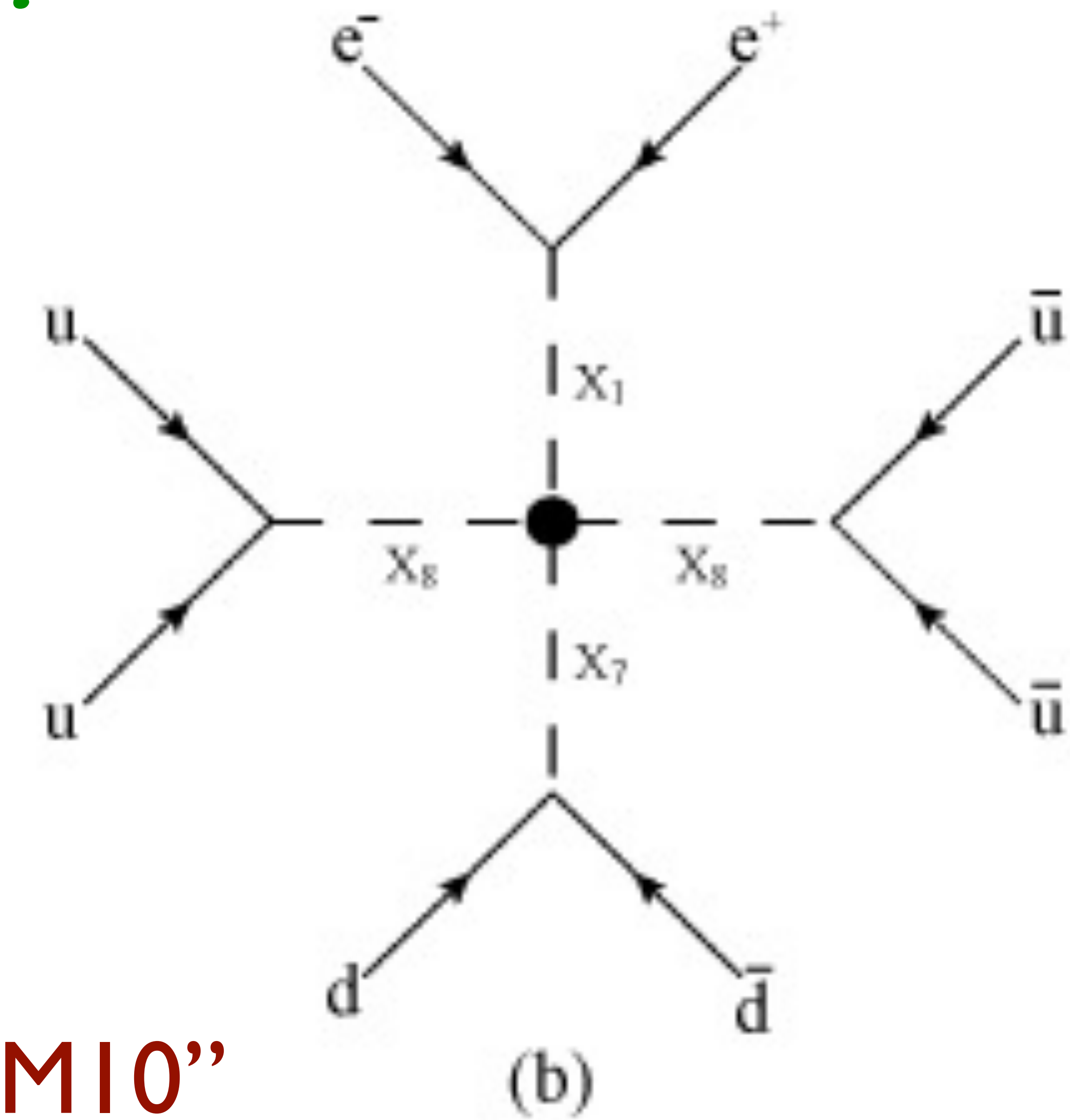
& w/ both can predict the existence of $\pi^-\pi^- \to e^-e^-$!

Connecting |ΔB|=2 to |ΔL|=2…

An example…



“M3”



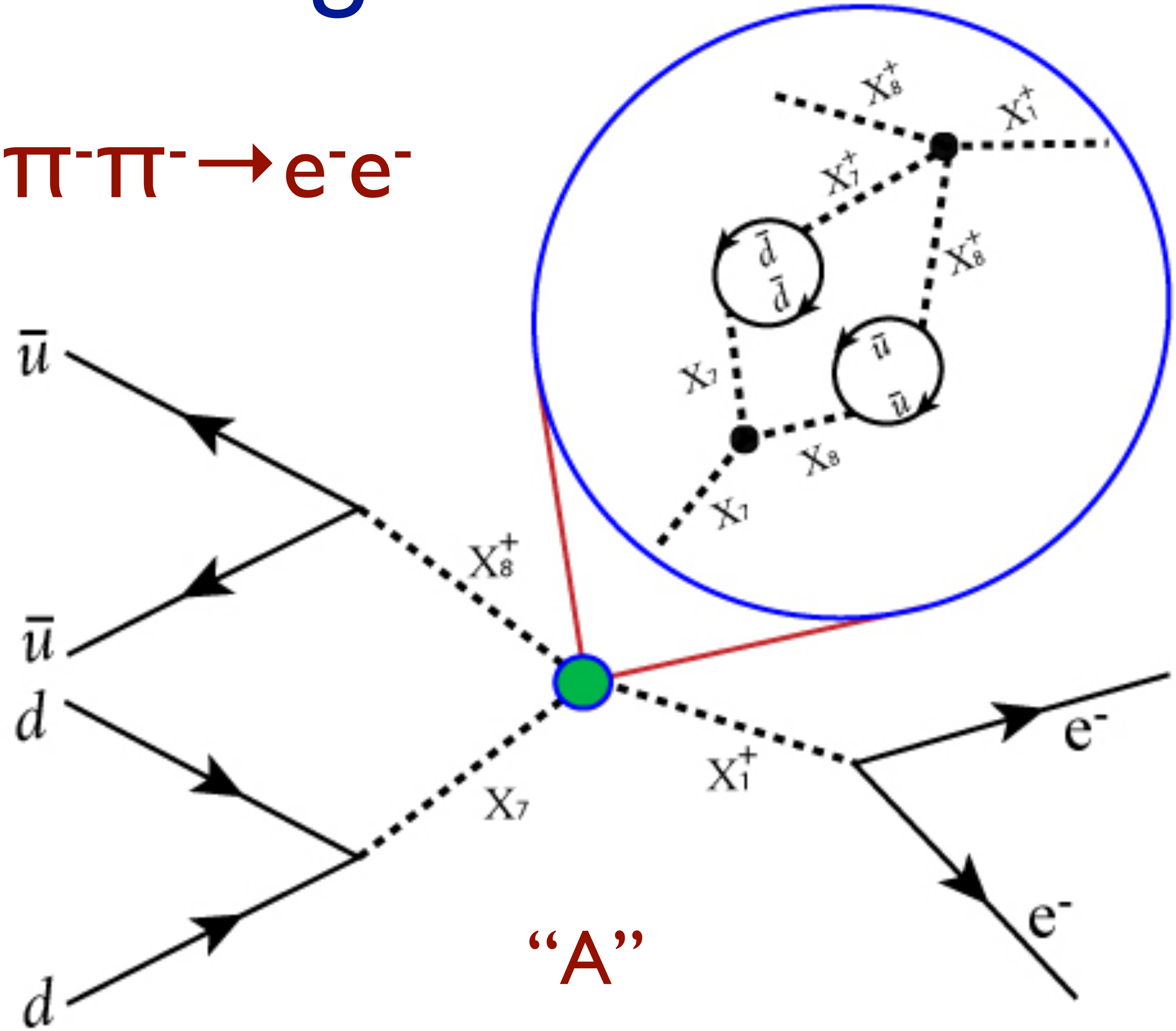
“M10”

n-$\bar{n}$

$e^- p \rightarrow e^+ \bar{p}$

Connecting |ΔB|=2 to |ΔL|=2…

$\pi^- \pi^- \rightarrow e^- e^-$



"A"

"Everything not forbidden is compulsory" [M. Gell-Mann, after T.H. White]

Patterns of |ΔB|=2 Violation

Discovery implications for 0ν ββ decay

TABLE IV. Possible patterns of $|\Delta \mathrm{B}| = 2$ discovery and their interpretation in minimal scalar-fermion models. Note that only $n - \bar{n}$ oscillations and $e^- n \to e^- \bar{n}$ break B-L symmetry and that the pertinent conversion processes can be probed through electron-deuteron scattering. The latter are distinguished by the electric charge of the final-state lepton accompanying nucleon-antinucleon annihilation. Note that the $0\nu\beta\beta$ query refers specifically to the existence of $\pi^-\pi^- \to e^-e^-$ from new, short-distance physics. Note that we can possibly establish model D and $|\Delta \mathrm{L}| = 2$ violation, but that model does not give rise to $\pi^-\pi^- \to e^-e^-$. In contrast we cannot establish X_8 alone and thus cannot establish model C.

Model	$n\bar{n}$?	$e^- n \to e^- \bar{n}$?	$e^- p \to \bar{\nu}_X \bar{n}$?	$e^- p \to e^+ \bar{p}$?	$0\nu\beta\beta$?
M3	Y	N	N	Y	Y [A]
M2	Y	Y	Y	Y	Y [B]
M1	Y	Y	Y	N	? [D]
–	N	N	Y	Y	? [C?]

Note high-intensity, low-energy e-scattering facilities (P2, e.g.) can be used to broader purpose

[SG & Xinshuai Yan, arXiv: 1808.05288]

Phenomenology of New Scalars

Constraints from many sources — Focus on first generation

i) n-$\bar{n}$ (But this does not impact M7)

ii) Collider constraints

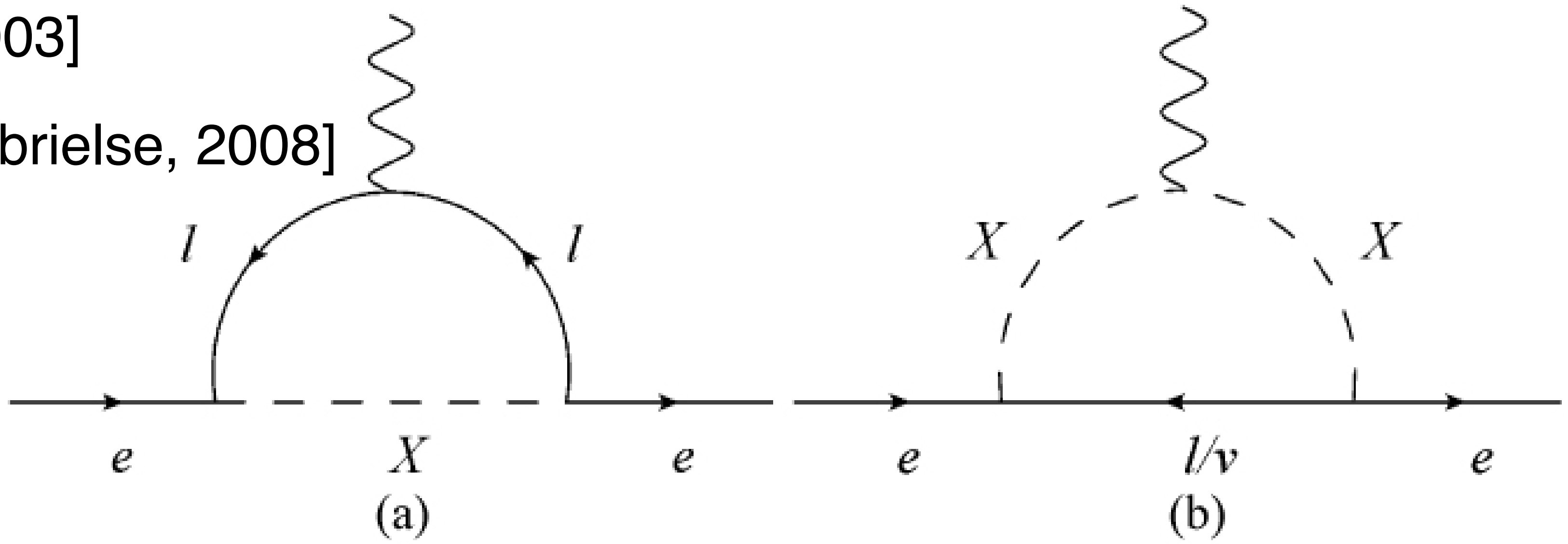
CMS: l^+l^+ search; cannot look at invariant masses below 8 GeV

[CMS 2012, 2014, 2016]

iii) $(g-2)_e$ [Babu & Macesanu, 2003]

Use latest exp't! [Hanneke, Fogwell, Gabrielse, 2008]

Limit: $M_1/g_1^{11} \geq 80$ GeV



iii) Nuclear stability

SuperK: $pp \rightarrow e^+e^+$

[Bramante, Kumar, & Learned, 2015]

But note short-distance repulsion!

iv) $H\bar{H}$ annihilation

[Grossman, Ng, & Ray, 2018]

But beware galactic magnetic fields!

Few GeV mass window possible

Low-Energy Electron Facilities

Illustrative parameter choices have been made

[Hydrogen]

Facility	Beam		Target		Luminosity
	Energy(MeV)	Current (mA)	Length (cm)	Density (g/cm^3)	(cm^{-2})
💡 CBETA [14]	150	40	60	0.55×10^{-6}	2.48×10^{36}
💫 MESA [15]	100	10	60	0.55×10^{-6}	6.21×10^{35}
💥 ARIEL [16]	50	10	100	0.09×10^{-3}	1.69×10^{38}
			* 0.2	71.3×10^{-3}	2.68×10^{38}
🎉 FAST [17]	150	28.8	100	0.09×10^{-3}	4.88×10^{38}
			* 0.1	71.3×10^{-3}	3.87×10^{38}

*Liquid

💡 = ERL (internal target)

💫 = ERL (e.g.)

💥 = Linac (external target)

🎉 = Linac, ILC test accelerator

Event Rates

Select particular scalar masses/couplings for reference

Rates in #/yr

$M'_{1,3}$ =3.5 GeV, else 2.5 GeV

$M_i' \equiv M_i/|g_i^{11}|^{1/2}$

$e^- p \to e^+ p$:

Facility	M7	M10	M11	M12	M14	M15	M16
CBETA [14]	0.076	0.010	0.001	0.001	0	0.053	0.006
MESA [15]	0.010	0.001	0.0	0.0	0	0.007	0.001
ARIEL [16]	0.800	0.107	0.014	0.007	0	0.558	0.065
	1.268	0.170	0.022	0.011	0	0.884	0.104
FAST [17]	14.908	1.998	0.259	0.124	0	10.398	1.217
	11.810	1.583	0.205	0.098	0	8.238	0.964

$e^- p \to \nu_e \bar{n}$

Facility	M7	M11	M14	M16
CBETA [14]	0.087	0.007	0	0.006
MESA [15]	0.011	0.001	0	0.001
ARIEL [16]	0.801	0.060	0	0.056
	1.270	0.096	0	0.088
FAST [17]	17.045	1.285	0	1.181
	13.503	1.018	0	0.935

N.B. conversion processes (also pertinent to $0\nu\beta\beta$) are discoverable

[SG & Xinshuai Yan, in preparation]

Summary

- The discovery of B-L violation would reveal the existence of dynamics beyond the Standard Model
- The energy scale of B-L violation speaks to different explanations as to why the neutrino is light — a "short range" mechanism could also generate B-L violation in the quark sector
- We have noted neutron-antineutron (& nucleon-antinucleon conversion!) conversion, i.e., neutron-antineutron transitions as mediated by an external current (as via scattering)
- We have used minimal scalar models to relate $|\Delta B|=2$ to $|\Delta L|=2$ processes
- Experiments with intense low-energy electron beams, e.g., complement essential neutron studies to help solve the ν mass puzzle

Backup Slides

B-L Violation via e-d scattering

What sorts of limits could be set?

Matching relation:

$$\eta\bar{v}(\mathbf{p}', s')C\not{j}\gamma_5 u(\mathbf{p}, s) = \frac{em}{3(p_{\rm eff}^2 - m^2)}\frac{ej_\mu}{q^2}$$

$$\times\langle\bar{n}_{\rm q}(\mathbf{p}',\mathbf{s}')|\int \mathbf{d^3x}\sum_{\mathbf{i},\chi_1,\chi_2,\chi_3}{}'(\delta_{\mathbf{i}})_{\chi_1,\chi_2,\chi_3}[(\tilde{\mathcal{O}}_{\mathbf{i}})^{\mathrm{R}\,\mu}_{\chi_1,\chi_2,\chi_3} - (\tilde{\mathcal{O}}_{\mathbf{i}})^{\mathrm{L}\,\mu}_{\chi_1,\chi_2,\chi_3}]|\mathbf{n}_{\rm q}(\mathbf{p},\mathbf{s})\rangle$$

The best limits come from small-angle scattering

— using the uncertainty principle to estimate θ_{min}

Sensitivity estimate for a beam energy of 20 MeV:

$$|\tilde{\delta}| \lesssim 2\times 10^{-15}\sqrt{\frac{N\ \text{events}}{1\ \text{event}}}\sqrt{\frac{1\ \text{yr}}{\text{t}}}\sqrt{\frac{0.6\times 10^{17}\ \text{s}^{-1}}{\phi}}\sqrt{\frac{1\ \text{m}}{L}}\sqrt{\frac{5.1\times 10^{22}\ \text{cm}^{-3}}{\rho}}\ \text{GeV}.$$

for the Majorana mass of the neutron

B-L Violation via n-d scattering

What sorts of limits could be set?

For cold neutrons (as at the ILL)

$$|\boldsymbol{p}_n| = 1.94 \text{ keV}$$

Sensitivity estimate (set by n-e scattering):

$$|\tilde{\delta}| \lesssim 3 \times 10^{-19} \sqrt{\frac{N \text{ events}}{1 \text{ event}}} \sqrt{\frac{1 \text{ yr}}{\text{t}}} \sqrt{\frac{1.7 \times 10^{11} \text{ s}^{-1}}{\phi}} \sqrt{\frac{1 \text{ m}}{L}} \sqrt{\frac{5 \times 10^{22} \text{ cm}^{-3}}{\rho}} \text{ GeV}$$

for the Majorana mass of the neutron

The combination of e and n beam experiments should offer a powerful crosscheck

Cross Section Estimate

Experimental limits can be translated to scalar-mass-coupling "sensitivity" plots

I st gen. $e^- p \to e^+ \bar{p}$

$$\sigma \sim 1.5 \times 10^{-4} |g_4^{11}|^6 |\lambda_7|^2 |g_3^{11}|^2 \left(\frac{5\,\mathrm{GeV}}{M_{X_4}} \right)^{12} \left(\frac{1\,\mathrm{GeV}}{M_{X_3}} \right)^{4} \mathrm{ab}$$

[SG & Xinshuai Yan, arXiv: 1808.05288]

Visible with "DarkLight" (FEL JLab) parameters

[Babu & Macesanu, 2003; Hanneke, Fogwell, Gabrielse, 2008]

N.B. survives direct limits: $(g\text{-}2)_e$;
observed H-atom stability

Constraints from muonium-antimuonium osc.; $|\Delta F|=2$ mixing removed by generation-dependent couplings