New Paths to B (and L) Violation by Two Units and Their Implications

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More Exotic B and L Violating Processes

(with Julian Heeck)
Subgroup of RF04

BLV circa 2020
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More Exotic B and L Violating Processes

We'll consider what wasn't discussed yesterday!

- I'll talk about breaking B and/or L by two (or more) units
- Julian Heeck's talk will include $|\Delta B|=1$ processes….

There are really very many possibilities, and several reach across subfield boundaries.

E.g., could the p be stable but the H-atom not?
[McKeen & Pospelov, 2003.02270]

What of H-$\bar{\mathrm{H}}$ oscillations? [Feinberg & Weinberg, 1961; Grossman, Ng, Ray, 2018]

I hope to review all (most?) of them, but first I think I should tell you why….

Perspective

Experiment & observation reveal
non-zero ν masses,
a cosmic BAU, dark matter, dark energy.

Although B violation appears in the SM (sphalerons),
[Kuzmin, Rubakov, & Shaposhnikov, 1985]
we know nothing of its pattern at accessible energies.

B and L violation could well play a role in solving all of these puzzles?

Experimental limits on $|\Delta B|=1$ processes are severe;
$|\Delta B|=2$ processes can be of distinct origin & important.
[Marshak and Mohapatra, 1980; Babu & Mohapatra, 2001 & 2012; Arnold, Fornal, & Wise, 2013]

Perspective, Part II

$|\Delta B|=2$ &/or $|\Delta L|=2$ interactions (w/ B-L violation) speak to fundamental Majorana dynamics

Both (and much more!) appear in a SO(10) GUT, e.g., but can they be connected with minimal ingredients?

[Arnold, Fornal, & Wise, 2013; Assad, Fornal, & Grinstein, 2018; SG & Yan, 2019]

Are there new ways of showing that a "Majorana ν" must exist?

[cf. Babu & Mohapatra, 2015 (plus N decay); SG & Yan, 2019]

This is distinct from finding an Majorana neutrino mass of observable size.

What role does flavor play?

Can dark matter can induce B and/or L violation?

A List of Possibilities

In addition to $n - \bar{n}$ oscillations, we could consider…

$\Lambda - \bar{\Lambda}$ oscillations (or other flavorful transitions)

NN decays to various final (dark?) states

scattering-mediated N$\bar{\text{N}}$ transitions

and/or

spin-dependent or CP-violating effects therein

collider searches for $|\Delta B|=|\Delta L|=3$ processes

In addition to 0ν ββ decay we could consider…

the role of light particle emission therein

$|\Delta L|=$(or >) 2 processes also with μ or τ final states

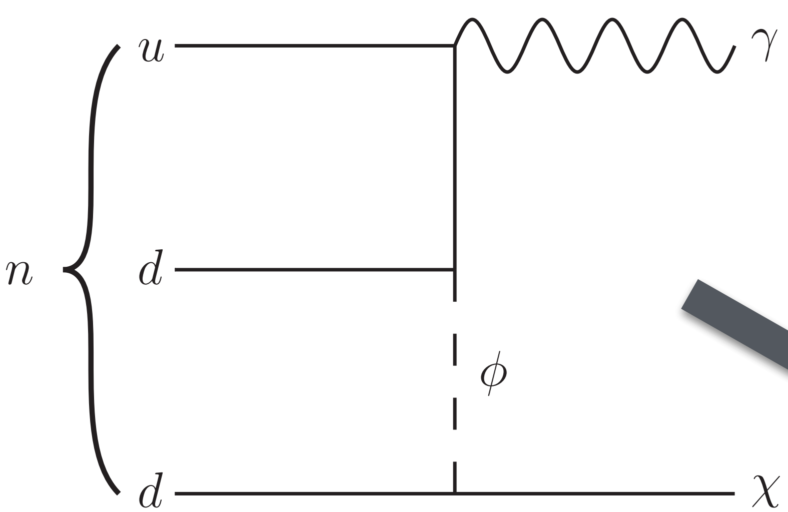
muonium-antimuonium oscillations *(a 2-fer!)*

$n - \bar{n}$ Oscillations, Dark Sectors, & CP Violation

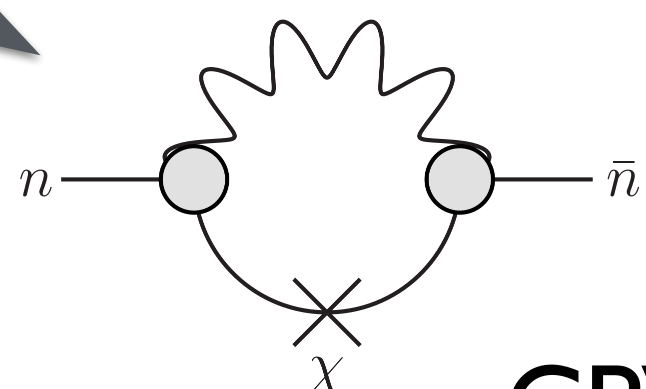
[McKeen & Nelson, 2016]

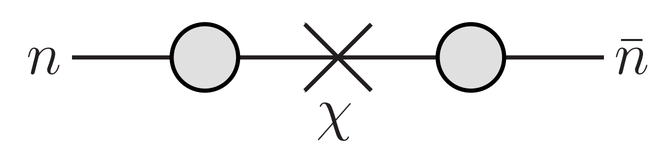
$$H = \begin{pmatrix} m_n - \frac{i}{2}\Gamma_n & M_{12} - \frac{i}{2}\Gamma_{12} \\ M_{12}^* - \frac{i}{2}\Gamma_{12}^* & m_n - \frac{i}{2}\Gamma_n \end{pmatrix}.$$

Appearance of CP violation requires nonzero Im$M_{12}\Gamma_{12}^*$



ϕ heavy





CPV effects very small

EDM signal?

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

If observed, the ν has a Majorana mass

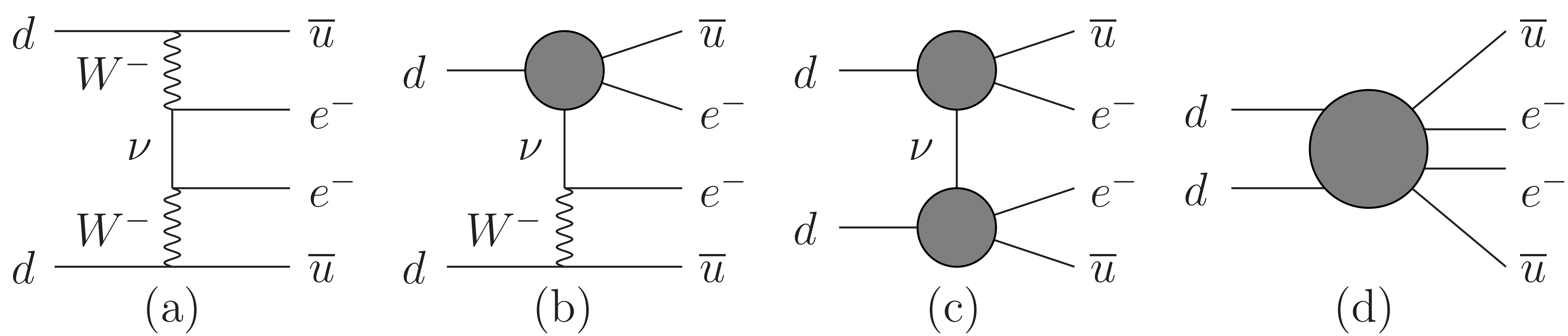
[Schechter & Valle, 1982]

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

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

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

"mass mechanism"



"long range"

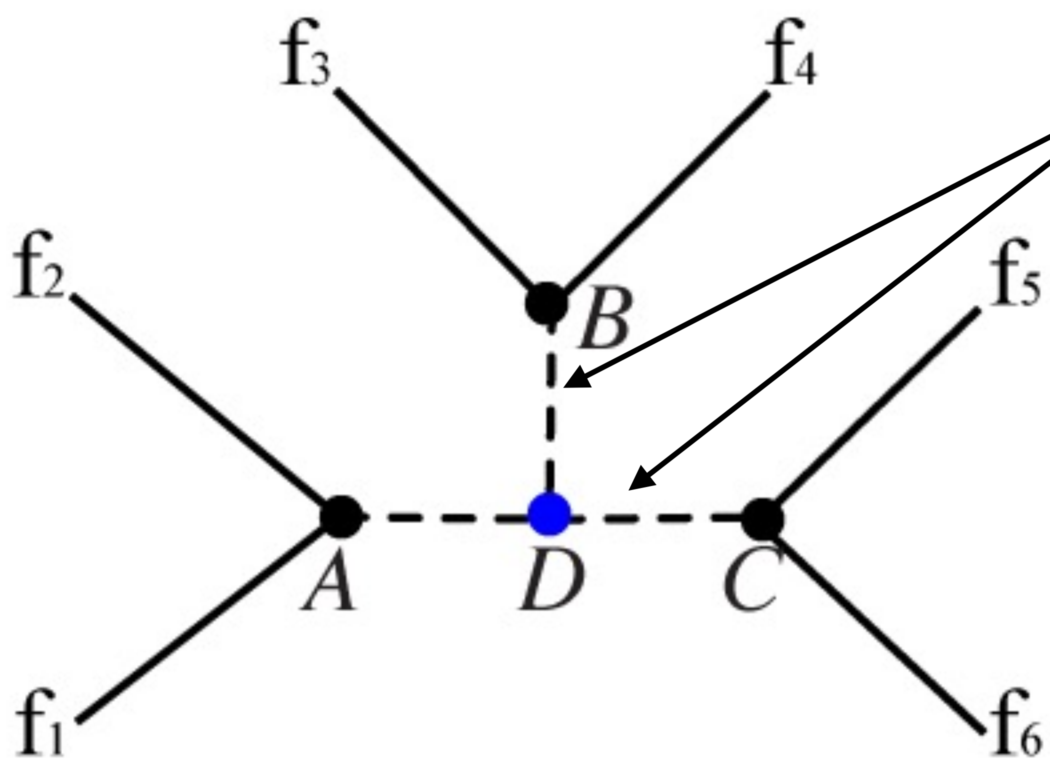
"short range"

[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, PLB 2019]

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 ★
  (mediated by external interactions) [SG & Xinshuai Yan, 2017]

(B-L need not be broken)

$n - \bar{n}$ & Nuclear Stability

n-$\bar{n}$ oscillations can be studied in bound or free systems.

New limits on dinucleon decay in nuclei have also recently been established.

[Gustafson et al., Super-K Collaboration, arXiv:1504.0104.]

$^{16}\mathrm{O}(pp) \to ^{14}\mathrm{C}\,\pi^+\pi^+$ has $\tau > 7.22 \times 10^{31}$ years at 90% CL.
$^{16}\mathrm{O}(pn) \to ^{14}\mathrm{N}\,\pi^+\pi^0$ has $\tau > 1.70 \times 10^{32}$ years at 90% CL.
$^{16}\mathrm{O}(nn) \to ^{14}\mathrm{O}\,\pi^0\pi^0$ has $\tau > 4.04 \times 10^{32}$ years at 90% CL.
Note $\tau_{NN} = T_{\mathrm{nuc}}\tau^2_{n\bar{n}}$ with $T_{\mathrm{nuc}} \sim 1.1 \times 10^{25}\mathrm{s}^{-1}$

Large suppression factors appear in all such nuclear studies, making free searches more effective. (at first glance)

In the case of bound n-$\bar{n}$ the suppression is set by

$$\frac{\delta^2}{(V_n - V_{\bar{n}})^2}$$

the difference in nuclear optical potentials. [Dover, Gal, and Richard; Friedman and Gal, 2008]

Now $^{16}\mathrm{O}(n{-}\bar{n})$ has $\tau > 1.9 \times 10^{32}$ years at 90% CL,
yielding $\tau_{n\bar{n}} > 2.7 \times 10^8$ s. [Abe et al., Super-K Collaboration, arXiv:1109.4227.]

Cf. free limit: $\tau_{n\bar{n}} \geq 0.85 \times 10^8\,\mathrm{s}$ at 90% C.L. [Baldo-Ceolin et al., ZPC, 1994 (ILL)]
with future improvements expected.

The nuclear suppression dwarfs that from magnetic fields.

Note recent EFT computations in d. [Oosterhof et al., 2019; Haidenbauer & Meissner 2020]

n - n̄ Transitions & Spin

Spin can play a role in a "mediated" process

A neutron-antineutron **oscillation** is a spontaneous process & thus the spin does not ever flip

However,

$$\mathcal{O}_4 = \psi^T C \gamma^\mu \gamma_5 \psi \, \partial^\nu F_{\mu\nu} + \text{h.c.}$$

$n(+) \to \bar{n}(-)$ occurs directly because the interaction with the current flips the spin.

This is concomitant with $n(p_1, s_1) + n(p_2, s_2) \to \gamma^*(k)$, for which only $L = 1$ and $S = 1$ is allowed via angular momentum conservation and Fermi statistics. [Berezhiani and Vainshtein, 2015]

Here $e + n \to \bar{n} + e$, e.g., so that the experimental concept for "$n\bar{n}$ conversion" would be completely different.

Effective Lagrangian

Neutron interactions with B-L violation & electromagnetism

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

magnetic moment

$n \to \bar{n}$ oscillation

$n \to \bar{n}$ conversion (spin!)

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

"spontaneous" → oscillation

[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]

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

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

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

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

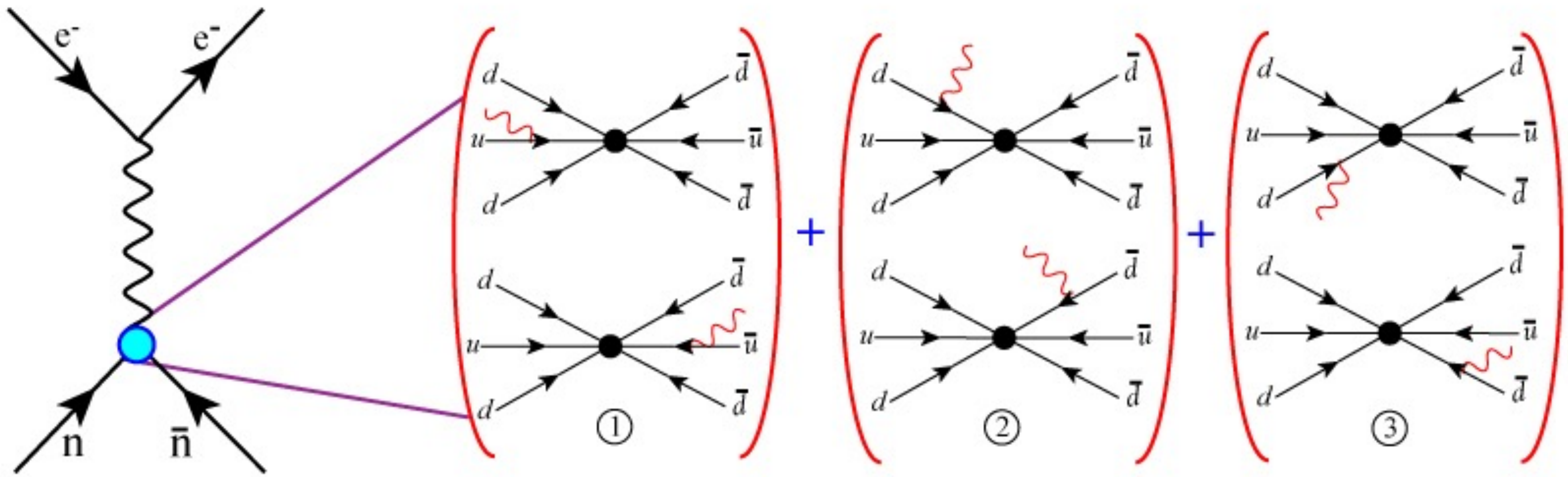
$$(\mathcal{O}_1)_{\chi_1 LR} = (\mathcal{O}_1)_{\chi_1 RL}, \qquad (\mathcal{O}_{2,3})_{LR\chi_3} = (\mathcal{O}_{2,3})_{RL\chi_3},$$ (but note Wagman, Buchoff, 2018)

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

- Only 4 appear in SM effective theory

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, 1983]

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

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

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 without N decay at tree level

Also choose X_i that respect SM gauge symmetry and also under interactions $X_i X_j X_k$ or $X_i X_j X_k X_l$, **etc.** — cf. "hidden portal" searches: possible parameters (masses, couplings) are limited by experiment

Scalars without Proton Decay

That also carry B or L charge

Scalar-fermion couplings

$Q_{em} = T_3 + Y$

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

Note powerful reduction of # of "short distance" mechanisms in 0νββ decay [X. Yan (DBD 2018) & SG]

[?: a⟷b symmetry]

Phenomenology of New Scalars

Constraints from many sources — Focus on first generation

i) n-$\bar{n}$

ii) Collider constraints

CMS: l^+l^+ search; cannot look at invariant masses below 8 GeV ATLAS: dijet studies "weaker"…

iii) P.V. Møller scattering Few GeV mass window possible

$M_{X_{1,3}}/g_{1,3}^{11} < 2.7$ TeV @ 90%CL [E158] (if "heavy")

iv) $(g\text{-}2)_e$ (superseded by Møller, save for light masses)

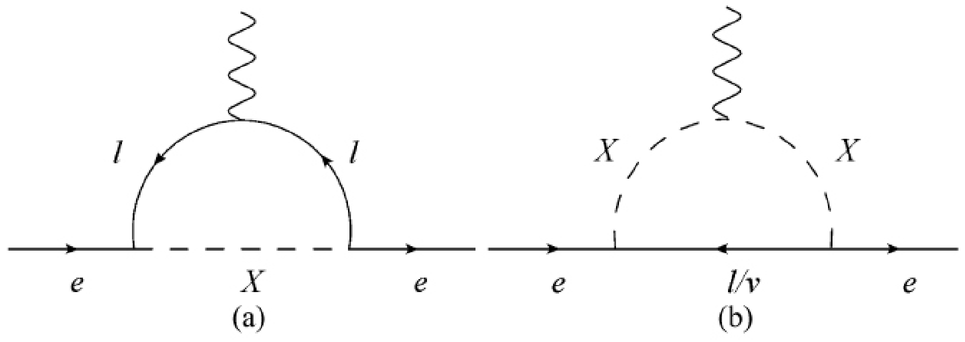
Light mass solution to Δa_e puzzle?

v) Nuclear stability [S.G. & Xinshuai Yan, 1907.12571]

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

vi) $H\bar{H}$ annihilation

Beware galactic magnetic fields!



A Sample Model

$$\mathcal{L}_{10} \supset -g_1^{ab} X_1 (e^a e^b) - g_7^{ab} X_7^{\alpha\beta} (d_\alpha^a d_\beta^b) - g_8^{ab} X_8^{\alpha\beta} (u_\alpha^a u_\beta^b)$$
$$-\lambda_{10} X_7^{\alpha\alpha'} X_8^{\beta\beta'} X_8^{\gamma\gamma'} X_1 \epsilon_{\alpha\beta\gamma} \epsilon_{\alpha'\beta'\gamma'} + \mathrm{H.c.}$$

Each term has mass dimension ≤ 4

But can generate a mass-dimension 12 operator at low energies to realize $e^- \, p \rightarrow e^+ \, \bar{p}$

There are several possible models.

Patterns of |ΔB|=2 Violation?

Note possible SM gauge invariant scalar models

[H.c. implied.]

[SG & Xinshuai Yan, arXiv: 1808.05288]

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	$X_4X_7X_7X_3^\dagger$

"4 X" models can yield $e^- p \to e^+ \bar{p}$

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

n-$\bar{n}$ (M1–M3) $\pi^-\pi^- \to e^-e^-$ (A–C)

[Models with |ΔL|=2 always involve 3 different scalars.]

Patterns of |ΔB|=2 Violation?

Note possible BNV processes

[SG & Xinshuai Yan, arXiv: 1808.05288]

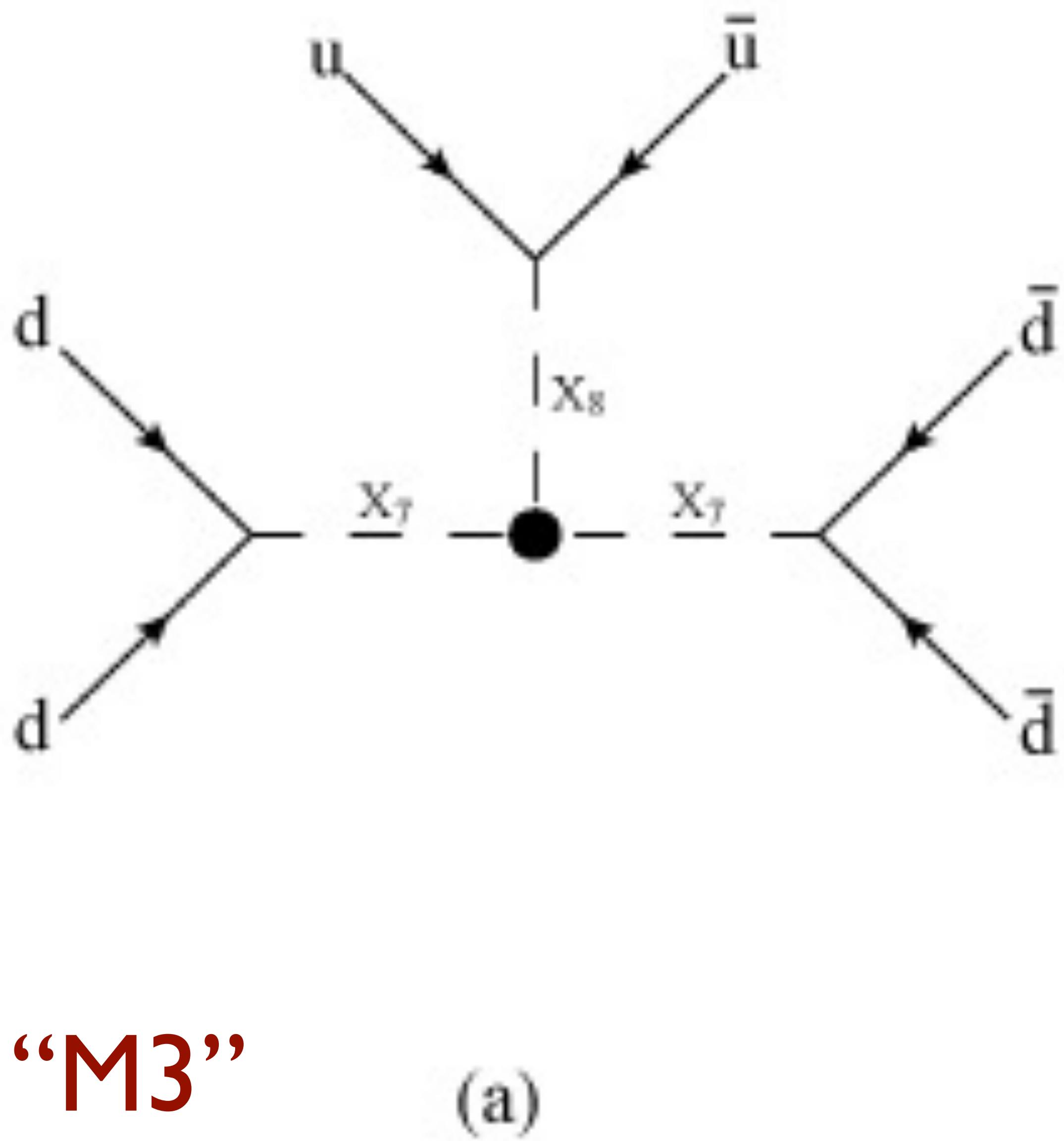
TABLE III. Suite of $|\Delta B| = 2$ and $|\Delta L| = 2$ processes generated by the models of Table II, focusing on states with first-generation matter. The $(*)$ superscript indicates that a weak isospin triplet of $|\Delta L| = 2$ processes can appear, namely $\pi^0\pi^0 \to \nu\nu$ and $\pi^-\pi^0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

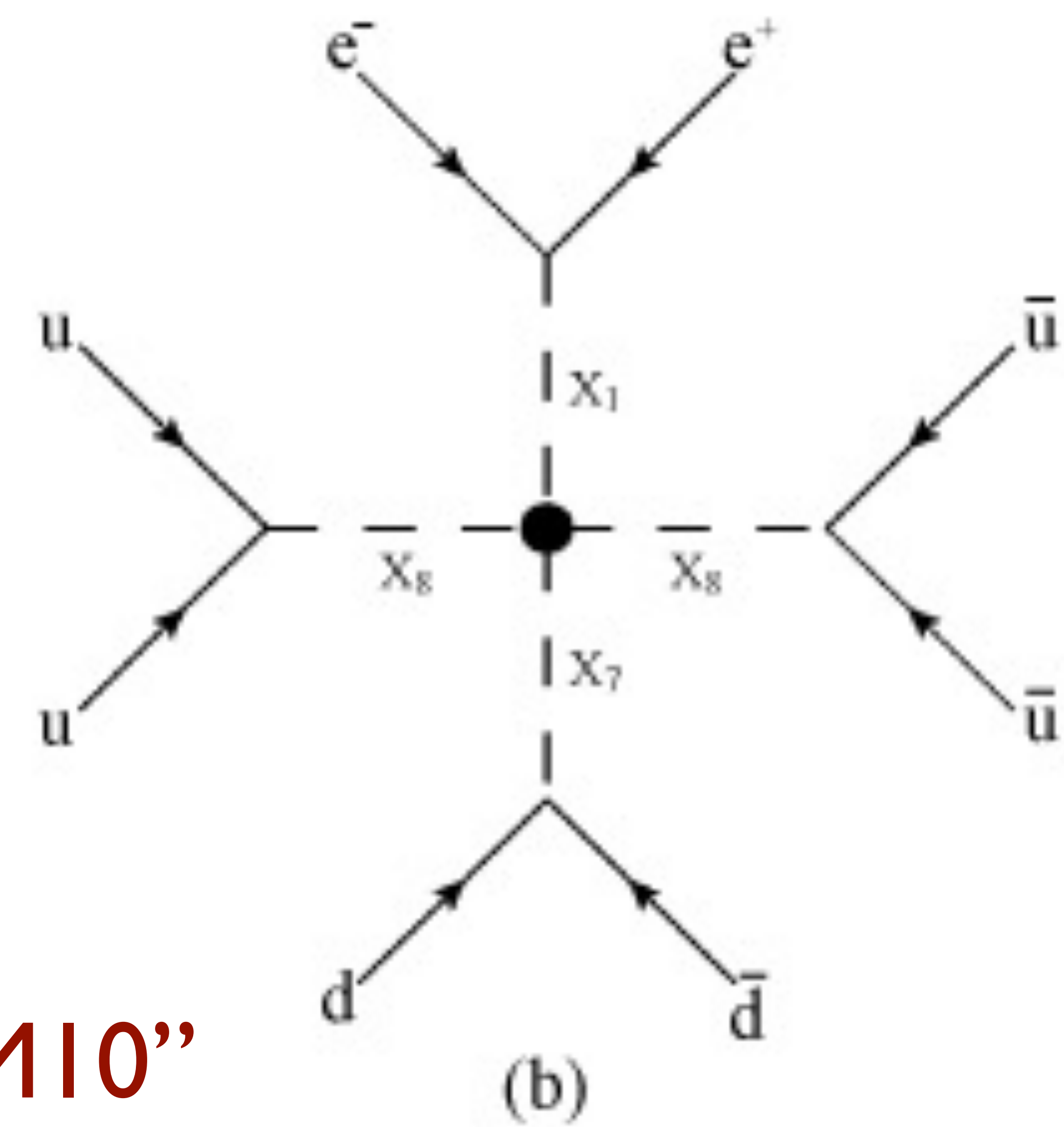
$n\bar{n}$	$\pi^-\pi^- \to e^-e^-$	$e^-p \to \bar{\nu}_{\mu,\tau}\bar{n}$	$e^-p \to \bar{\nu}_e\bar{n}/e^+\bar{p}$	$e^-p \to e^+\bar{p}$
M1	A	M5	M7	M10
M2	$B^{(*)}$	M6	M11	M12
M3	$C^{(*)}$	M13	M14	M15
			M16	

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-n̄

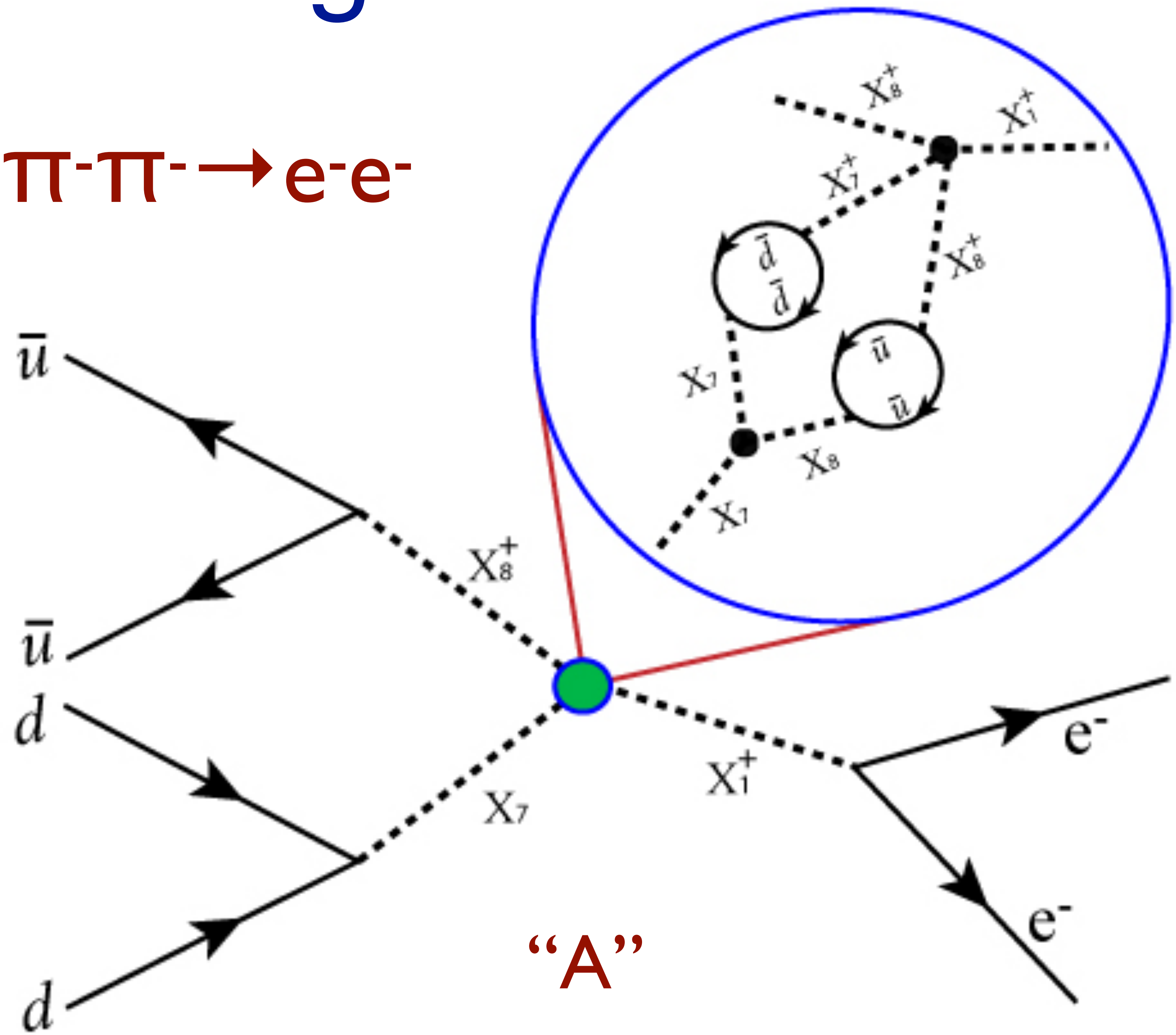
"Oscillation"

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

"Conversion"

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

S.G. & Xinshuai Yan, PRD 2018 [arXiv:1710.09292]

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?]

Patterns of observation can distinguish the possibilities.

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

[SG & Xinshuai Yan, arXiv: 1808.05288]

Low-Energy Electron Facilities

Note illustrative parameter choices

[Hydrogen]

	Facility	Beam: Energy(MeV)	Beam: Current (mA)	Target: Length (cm)	Target: Density (g/cm^3)	Luminosity (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

💡 = proposed, ERL (internal target)

💫 = ERL (e.g.)

💥 = Linac (external target)

🎉 = Linac, ILC test accelerator

Use E=40 MeV for estimates.

Event Rates

Select particular scalar masses/couplings for reference

$\lambda_i = 1 \quad M_{Xi}/g_i^{1/2} = 30$ GeV for $i = 1,2,3$ else 1GeV

Rates in #/yr

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

Facility	M7	M10	M11	M12	M14	M15	M16
CBETA [18]	1.12	0.18	0.01	0.00	0	2.24	0.45
MESA [19]	0.28	0.05	0.00	0.00	0	0.56	0.11
ARIEL [20]	76.41	12.59	0.41	0.20	0	152.69	30.68
	121.06	19.95	0.65	0.31	0	241.93	48.62
FAST [21]	220.05	36.27	1.18	0.56	0	439.75	88.37
	174.33	28.73	0.93	0.45	0	348.38	70.00

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

Facility	M5	M6	M7	M11	M13	M14	M16
CBETA [18]	0.00	0	0.08	0.00	0.14	0	0.02
MESA [19]	0.00	0	0.02	0.00	0.03	0	0.01
ARIEL [20]	0.03	0	5.17	0.24	9.45	0	1.59
	0.04	0	8.19	0.38	14.97	0	2.51
FAST [21]	0.08	0	14.88	0.70	27.20	0	4.57
	0.06	0	11.79	0.55	21.55	0	3.62

 [S.G. & Xinshuai Yan, **in preparation**]

Summary

- The discovery of B-L violation would reveal the existence of dynamics beyond the Standard Model. **There are several interesting experiments, that complement $n - \bar{n}$ oscillation and 0ν ββ decay searches.**
- Minimal scalar models can relate |ΔB|=2 to |ΔL|=2 processes [i.e., via the "short range" mechanism of 0νββ decay]
- We have noted nucleon-antinucleon conversion processes, i.e., scattering-mediated nucleon-antinucleon processes, in addition to **neutron-antineutron oscillations**, to establish an effective Majorana ν
- Such a connection does not establish the observed scale of the neutrino mass, nor the mechanism of 0νββ decay; thus direct empirical studies continue to be **essential**
- Experiments with intense low-energy electron beams, e.g., complement essential neutron studies to help solve the ν mass puzzle

Backup Slides

Fundamental Majorana Dynamics

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

Lorentz invariance allows

$$\mathcal{L} = \bar{\psi} i \not{\partial} \psi - \frac{1}{2} m (\psi^T C \psi + \bar{\psi} C \bar{\psi}^T)$$

[Majorana, 1937]

where m is the Majorana mass.

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

Based on work in collaboration with Xinshuai Yan (U. Kentucky→CCNU)

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

Neutron-Antineutron Oscillation

Quark-level operators

[Rao & Shrock, 1982]

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

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

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

Note

$O_2 \to O_3$

$T_s \to T_a$

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

- 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

From Oscillation to Conversion

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

$$\mathcal{H}_I \supset \frac{\delta_q}{2}\sum_{\chi_1}(\psi^{\rho T}_{\chi_1}C\psi^{\delta}_{\chi_1} + \bar{\psi}^{\delta}_{\chi_1}C\bar{\psi}^{\rho T}_{\chi_1}) + Q_\rho e\sum_{\chi_2}\bar{\psi}^{\rho}_{\chi_2}A\!\!\!/\psi^{\rho}_{\chi_2} + Q_\delta e\sum_{\chi_3}\bar{\psi}^{\delta}_{\chi_3}A\!\!\!/\psi^{\delta}_{\chi_3},$$

flavor

chiral basis

matrix element:

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

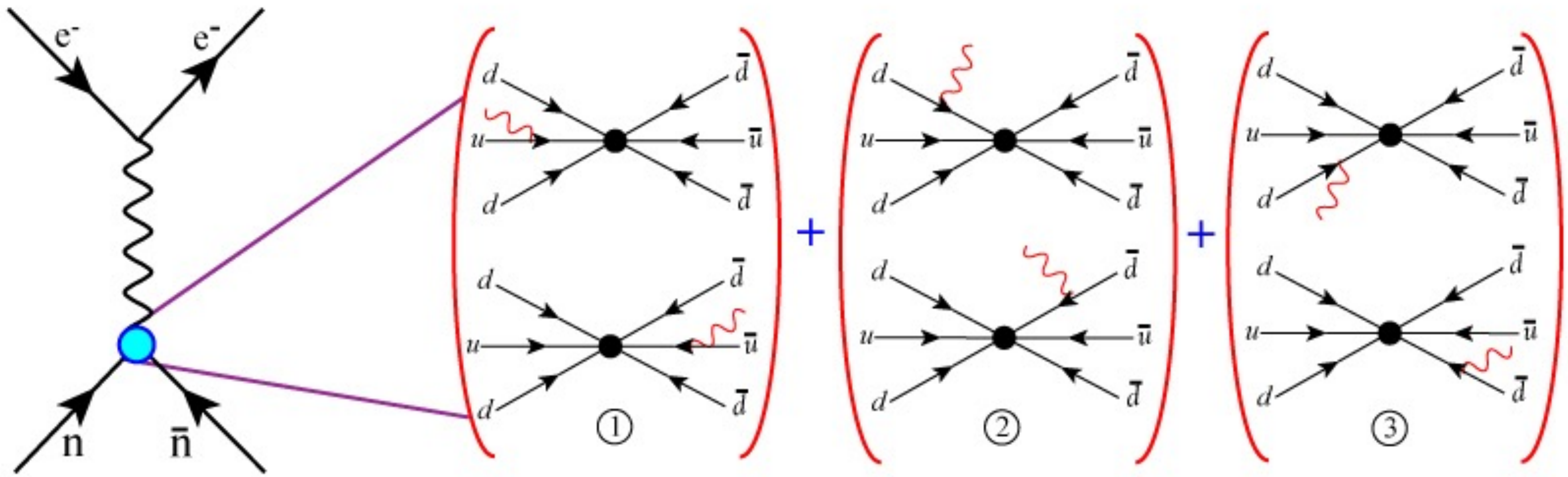
- if $\delta=\rho$ yields $C\gamma_\mu\gamma_5$ only

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, 1983]

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

B-L Violation via e-n scattering

Linking neutron-antineutron oscillation to conversion

Moreover…

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

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 $n-\bar{n}$ conversion from O_2 and O_3 operators only!

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

B-L Violation via e-d scattering

What sorts of limits could be set?

Matching relation:

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

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

The best limits come from small-angle scattering

— using the uncertainty principle to estimate $\theta_{\rm min}$

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

Based on work in collaboration with Xinshuai Yan (U. Kentucky→CCNU)

Research supported by the U.S. Dept. of Energy Office of Nuclear Physics
under DE-FG02-96ER40989

Perspective

An $(g\text{-}2)_e$ "anomaly" is a very new thing! (t > 2011)

The measurement of $a_e \equiv (g\text{-}2)_e/2$ was once the only way to determine the fine-structure constant α precisely

[… Hanneke, Fogwell, Gabrielse, 2008]

Now with h/M_X (for X=Rb or Cs) from
atom interferometry
we have another precise way of determine α

[Bouchendira et al., 2011 [Rb]; Parker et al., 2018 [Cs]]

Thus now both a_e and a_μ probe physics BSM!

a_μ and a_e Probe Physics Beyond the SM

[Aoyama, Kinoshita, Nio, 2019]

$$a_e^{EXP} - a_e^{SM}\ [\mathrm{Rb}] = (-131 \pm 77) \times 10^{-14}$$

$$a_e^{EXP} - a_e^{SM}\ [\mathrm{Cs}] = (-88 \pm 36) \times 10^{-14}$$

$\sim 2.4\sigma$

$$a_\mu^{EXP} - a_\mu^{SM} = (2.74 \pm 0.73) \times 10^{-9}$$

(!)

$\sim 3.7\sigma$

Both the relative sign and size are important.

A viable new-physics solution cannot distinguish μ and e only by their mass! (Δa_e is 10x too big!)

a_μ & a_e Signal
Lepton Flavor Universality (LFU) Violation

"LFU" means that μ and e differ only in their mass

$$(\delta a_f)_{\mathrm{new}} \sim m_f^{\,2} \,/\, M_{new}^2$$

Note $m_\mu^2/m_e^2 \sim 4.2\mathrm{x}10^4$

Thus Δa_e [Cs,Rb] implies Δa_μ $\Rightarrow\Leftarrow$ BNL E821!

Thus LFU is violated

This also suggests the appearance of
"light" new physics

Interpreting Δa_μ & Δa_e

Challenging to explain both at once

BSM solutions must treat μ and e differently

Some Possibilities

i) a single, real scalar φ; but introduce e-φ couplings to drive Barr-Zee graph for a_e [Davoudiasl & Marciano, 2018]

ii) Models with Lμ-Lτ symmetry… [Crivellin et al., 2018]

iii) Models that stabilize the Higgs sector… [Hiller et al., 2019]

iv) A complex scalar with CP-odd couplings to e but CP-even couplings to μ [Liu, Wagner, Wang, 2018]

(Similar, e.g., to other Δa_μ solutions)

Models with axial vector bosons can explain sign of Δa_e

[Fayet, 2007; Kahn et al., 2017]

A New Interpretation of Δa_e

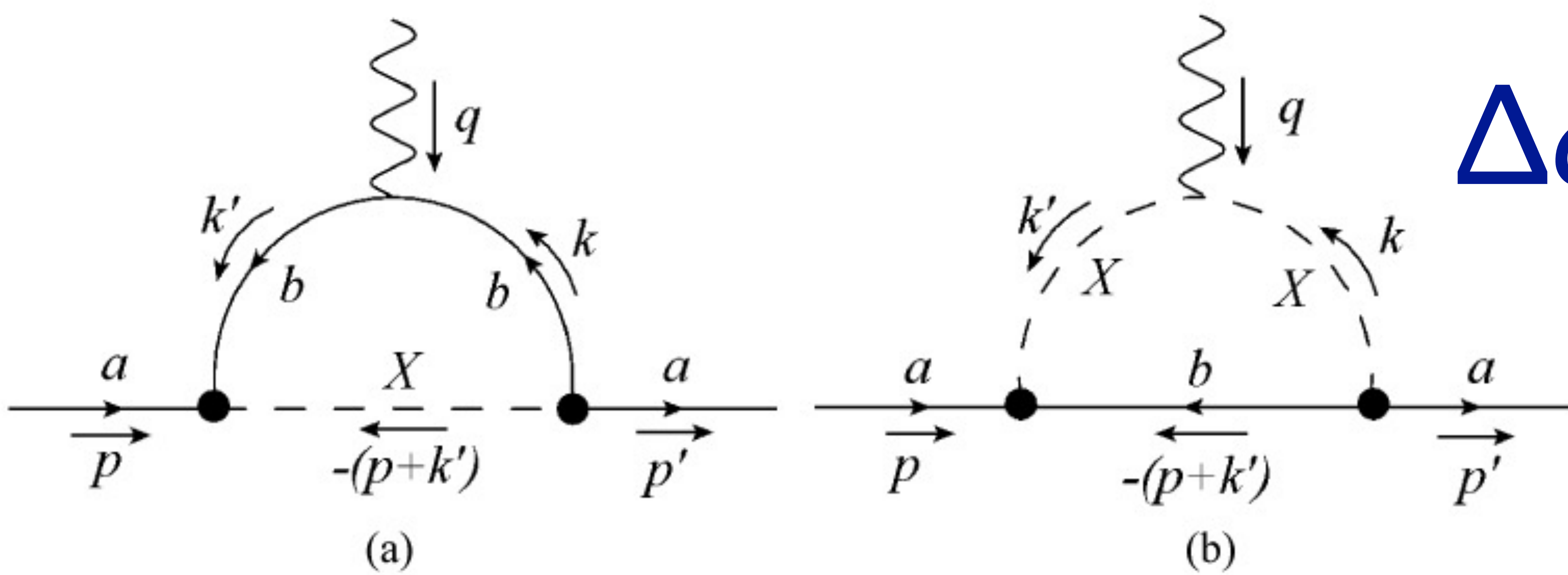
Enter Lepton-Number-Carrying Scalars

[SG & Yan, 2019]

We adopt minimal scalar models previously used for the study of baryon & lepton number violation [Arnold, Fornal, & Wise, 2013 & 2013; SG & Yan, PLB 2019]

Proton decay evaded by quantum number assignment

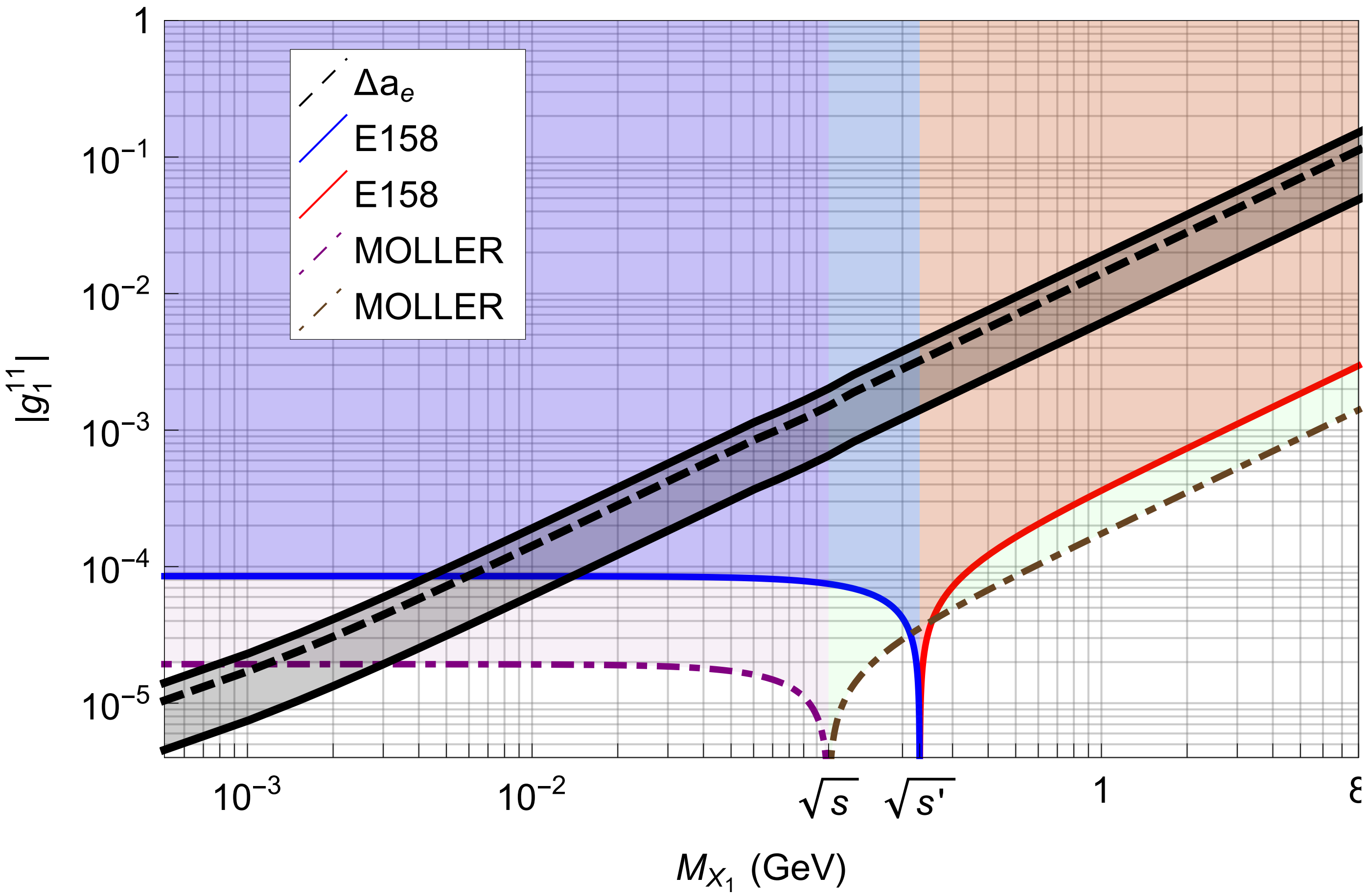
No "secret ingredients"!



$\Delta a_e < 0!$

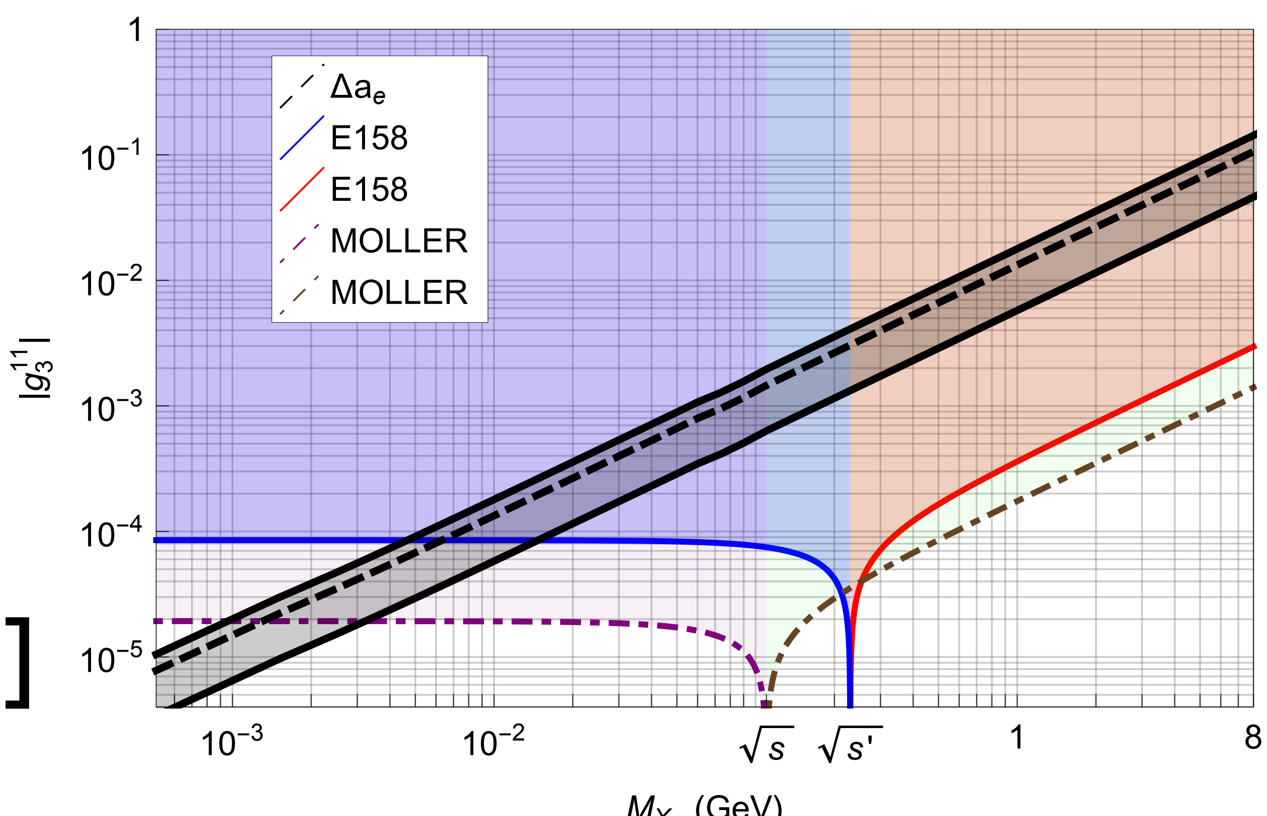
Δa_e Solutions Confront PVES

Doubly Charged Scalars Appear in s-Channel



X1

X3

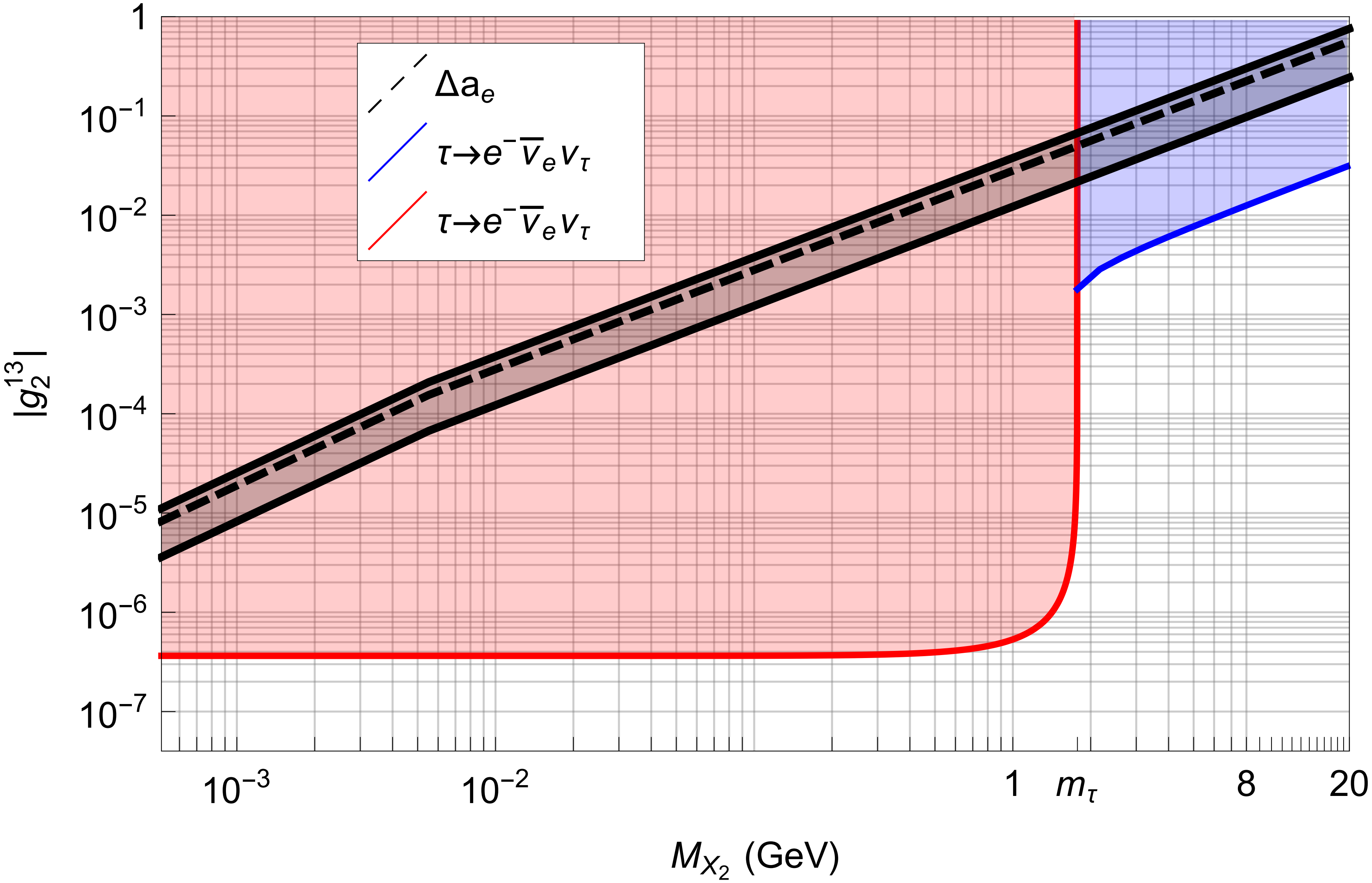


[S.G. & Xinshuai Yan, 1907.12571]

Also subject to (KLOE-2) α running constraint

Δa_e Solutions Confront τ Decay

Scalar X_2 cannot explain the anomaly



Thus the possible Δa_e solutions are somewhat limited; employ "heavy" limits in what follows….