Searches for scalars that carry B or L, taken broadly: whither and wherefore

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Theoretical Innovations for Future Experiments Regarding Baryon Number Violation, Part I
(Virtually) ACFI UMass
August 6, 2020

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]

Today*

— I argue that new, possible avenues for B (& L) NV (by 2 units) have been largely overlooked

— That light hidden sectors that could help mediate mass rare processes associated with dim ≥ 9 operators are not excluded by existing experiments

— I discuss the existing constraints & the discovery potential of some possible new experiments

— These possibilities strengthen interest in $|\Delta B| = 2$ experiments of increased sensitivity!

*based on work in collaboration with Xinshuai Yan (CCNU, Wuhan)

“What’s Past is Prologue”

We look down from the GUT scale to find $|\Delta B|=2$ processes

Note limits on $|\Delta B|=1$ processes are severe!

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

It had long been thought that BNV is fantastically suppressed, making $n\bar{n}$ oscillations very challenging to observe

Enter SO(10) models [Babu, Mohapatra]

Enter new scalars….

What is the value of the “partial unification” scale?

The idea that BNV (& LNV) is intrinsically *very* HE physics has colored experimental searches

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 $X_iX_jX_k$ or $X_iX_jX_kX_l$, **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^ae^b	[S]
X_2	$(1,1,1)$	0	-2	XL^aL^b	[A]
X_3	$(1,3,1)$	0	-2	XL^aL^b	[S]
X_4	$(\bar{6},3,-1/3)$	-2/3	0	XQ^aQ^b	[S]
X_5	$(\bar{6},1,-1/3)$	-2/3	0	XQ^aQ^b, Xu^ad^b	[A,–]
X_6	$(3,1,2/3)$	-2/3	0	Xd^ad^b	[A]
X_7	$(\bar{6},1,2/3)$	-2/3	0	Xd^ad^b	[S]
X_8	$(\bar{6},1,-4/3)$	-2/3	0	Xu^au^b	[S]
X_9	$(3,2,7/6)$	1/3	-1	$X\bar{Q}^ae^b, XL^a\bar{u}^b$	[–,–]

Note SU(3) rep'ns

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

[?: a⟷b symmetry]

A Sample Model

$$\mathscr{L}_{1,7,8} \supset -g_1^{ab} X_1 (e^a e^b) - g_7^{ab} X_7^{\alpha\beta} (d_\alpha^a d_\beta^b) - g_8^{ab} X_8^{\alpha\beta} (u_\alpha^a u_\beta^b)$$
$$-\underline{\lambda_3 X_7^{\alpha\alpha'} X_7^{\beta\beta'} X_8^{\gamma\gamma'} \epsilon_{\alpha\beta\gamma} \epsilon_{\alpha'\beta'\gamma'}} - \underline{\lambda_{10} X_7^{\alpha\alpha'} X_8^{\beta\beta'} X_8^{\gamma\gamma'} X_1 \epsilon_{\alpha\beta\gamma} \epsilon_{\alpha'\beta'\gamma'}}$$
$$-\underline{\lambda_A X_8^{\alpha\alpha'} (X_7^{\alpha\alpha'})^\dagger X_1} + \mathrm{H.c.}$$

Each term has mass dimension ≤ 4

But can generate higher mass-dimension operators at low energies to realize $\underline{n\bar{n}\ \text{oscillations}}$, $\underline{e^- p \to e^+ \bar{p}}$, and $\underline{\pi^- \pi^- \to e^- e^-}$ $(0\nu\beta\beta)$ processes

The visibility of these processes is determined by the scalar masses and couplings.

Other models, and other connections, are possible.

Flavor Physics Constraints

Would seem to push new scalars to high scales

An example with two $\bar{6}'s$: [Arnold, Fornal, Wise, PRD, 2013]

$$\mathscr{L}_{5,7} \supset -g_5^{ab} X_5^{\alpha\beta}(Q_\alpha^a \varepsilon Q_\beta^b) - g'^{ab}_5 X_5^{\alpha\beta}(u_\alpha^a d_\beta^b) - g_7^{ab} X_7^{\alpha\beta}(d_\alpha^a d_\beta^b)$$

$$-\underline{\lambda_1 X_5^{\alpha\alpha'} X_5^{\beta\beta'} X_7^{\gamma\gamma'} \epsilon_{\alpha\beta\gamma}\epsilon_{\alpha'\beta'\gamma'}}$$

Could choose $M_7 \gg M_5$!

- supports <u>$n\bar{n}$ oscillations</u>

$$|\delta| = \langle \bar{n} | \mathscr{H}_{\text{eff}} | n \rangle \approx \frac{2\lambda_1 \beta^2 |(g'^{11}_5)^2 g_7^{11}|}{3 M_5{}^4 M_7{}^2}$$

$|\delta| \to M_5 = M_7 \gtrsim 500\,\text{TeV}$

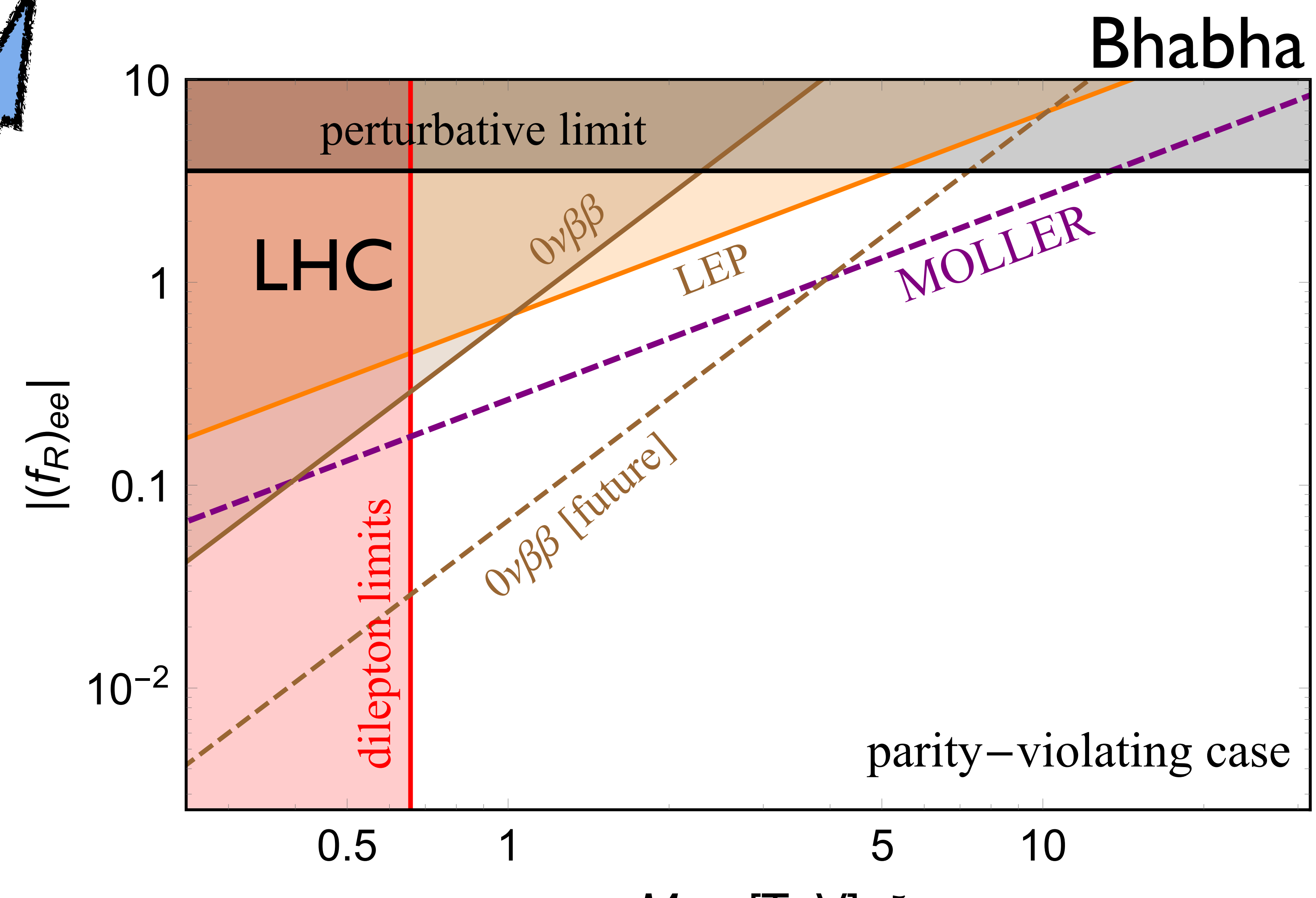
- X_5 itself has L, R couplings & thus yields a large n EDM contribution at one-loop via the t quark ["light" $M_5 \implies \varphi_{\text{CP}} \ll 1$]
- X_5 also yields $K^0 - \bar{K}^0$ and $D^0 - \bar{D}^0$ mixing
- X_7 itself contributes to $K^0 - \bar{K}^0$ mixing

An alternate solution is to pick the flavor structure of the couplings.

Doubly-Charged Higgs Constraints

R (or L)-handed SU(2) triplets that carry lepton #

X_3



[Dev, Ramsey-Musolf, Zhang, PRD, 2018]

But what are the constraints on X_1 and X_3?
Are lighter masses possible?
CMS search; cannot look at l^+l^+ invariant masses < 8 GeV

Bhabha Scattering

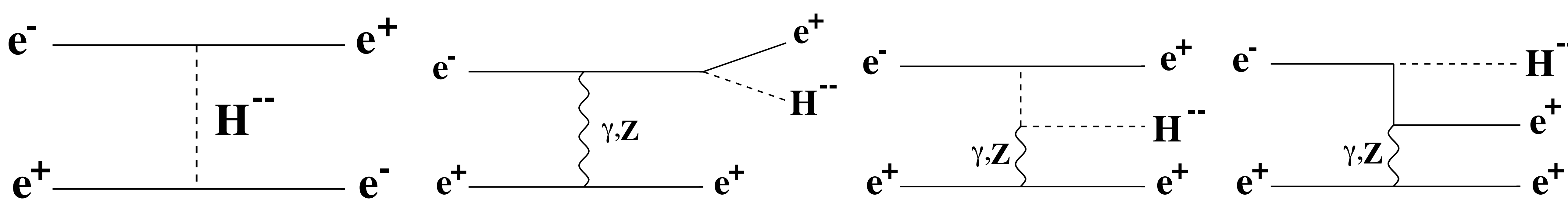
Constrains doubly charged scalars (here H^{--})

[Abbiendi et al., OPAL, PLB, 2003]

Abstract:

A search for the single production of doubly-charged Higgs bosons is performed using e^+e^- collision data collected by the OPAL experiment at centre-of-mass energies between 189 GeV and 209 GeV. No evidence for the existence of $H^{\pm\pm}$ is observed. Upper limits are derived on h_{ee}, the Yukawa coupling of the $H^{\pm\pm}$ to like-signed electron pairs. A 95% confidence level upper limit of $h_{ee} < 0.071$ is inferred for $M(H^{\pm\pm}) < 160$ GeV assuming that the sum of the branching fractions of the $H^{\pm\pm}$ to all lepton flavour combinations is 100%. Additionally, indirect constraints on h_{ee} from Bhabha scattering at centre-of-mass energies between 183 GeV and 209 GeV, where the $H^{\pm\pm}$ would contribute via t-channel exchange, are derived for $M(H^{\pm\pm}) < 2$ TeV. These are the first results both from a single production search and on constraints from Bhabha scattering reported from LEP.

Indirect Direct



The measured differential cross-sections are fitted with the theoretical prediction using a χ^2 fit. The fit is performed for fixed values of the doubly-charged Higgs boson mass between 80 GeV and 2000 GeV, allowing the square of the coupling, h^2_{ee}, to vary. Although only $h^2_{ee} > 0$

lower assumed mass limit in each case

Pair Production Search

Constrains doubly charged scalars (here $H^{\pm\pm}$)

$$e^+e^- \to H_L^{++}H_L^{--} \quad (\neq) \quad e^+e^- \to H_R^{++}H_R^{--}$$

Abstract: $H^{\pm\pm} \to \ell^\pm\ell^\pm$ [Abbiendi et al., OPAL, PLB, 2001]

A search for pair-produced doubly charged Higgs bosons has been performed using data samples corresponding to an integrated luminosity of about 614 pb^{-1} collected with the OPAL detector at LEP at centre-of-mass energies between 189 GeV and 209 GeV. No evidence for a signal has been observed. A mass limit of 98.5 GeV/c^2 at the 95% confidence level has been set for the doubly charged Higgs particle in left-right symmetric models. This is the first search for doubly charged Higgs bosons at centre-of-mass energies larger than 91 GeV.

The simulation of the signal events with one non-zero $h_{\ell\ell'}$ coupling at a time and with zero lifetime has been done with the Monte Carlo generator PYTHIA [14] modified according to [5]. $H^{++}H^{--}$ events have been generated for various mass points ranging from 45 GeV/c^2 to half the centre-of-mass energy, $\sqrt{s}$. At each point on the $(M_H,\sqrt{s})$ plane, 10000 events for each of the six $H^{\pm\pm} \to \ell^\pm\ell^\pm$ decays have been generated.

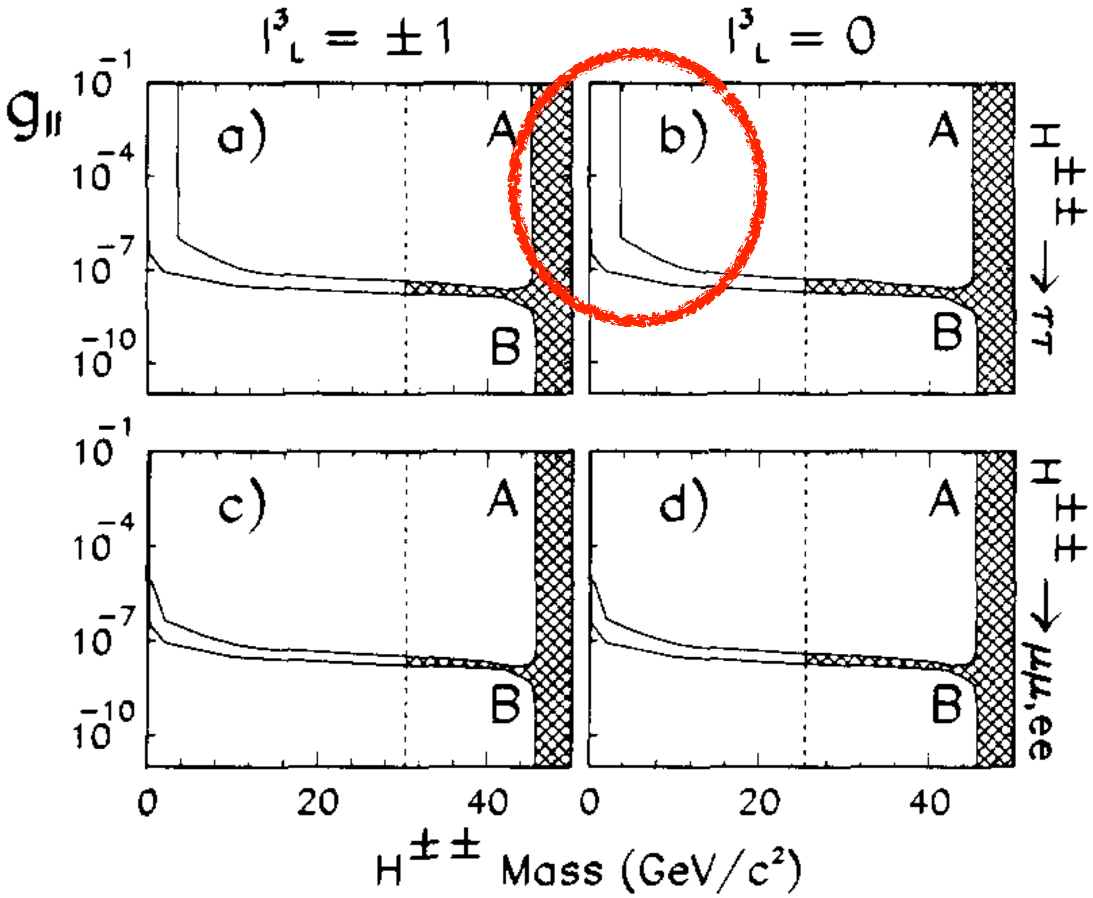
lower assumed mass limit based on Z^0 decay

A search for the decay of the Z^0 into doubly charged Higgs bosons ($H^{\pm\pm}$) decaying to same-sign lepton pairs is presented using data collected with the OPAL detector at LEP, with an integrated luminosity of 6.8 pb^{-1}. Four-track final states from prompt decays, and events with at least one highly ionizing track from long-lived $H^{\pm\pm}$ were sought. $H^{\pm\pm}$ are excluded in the mass range from zero to 45.6 GeV/c^2 and for a coupling constant range that extends down to zero.

They study all I_3^L states! [Acton et al., OPAL, PLB, 1992]

Z Decay Studies

[Acton et al., OPAL, PLB, 1992]



limit. The difference between the measurement and the prediction is less than 40 MeV/c^2 at the 95% confidence level. The bound on the $H^{\pm\pm}$ width is obtained by setting the partial width for $Z^0 \to H^{++}H^{--}$ to 40 MeV/c^2 which yields a lower bound of 25.5 GeV/c^2 for $I_3^L = 0$, and 30.4 GeV/c^2 for $I_3^L = \pm 1$.

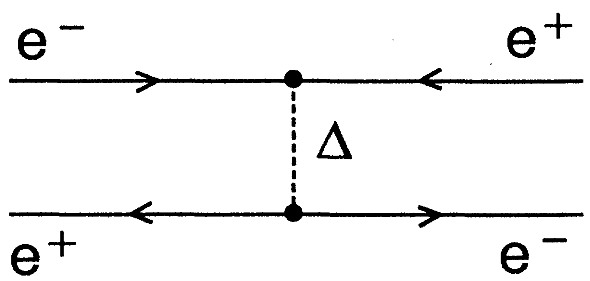
Fig. 3. The $H^{\pm\pm}$ exclusion regions in the M_H–$g_{\ell\ell}$ plane. The unhashed zones show the regions excluded at the 95% confidence level. The regions labeled by "A" are excluded by the search for the short-lived $H^{\pm\pm}$. Those labeled by "B" (which extend down to $g_{\ell\ell} = 0$) are excluded by the search for the long-lived $H^{\pm\pm}$. $H^{\pm\pm}$ with mass less than 25.5 GeV/c^2 ($I_3^L = 0$) or 30.4 GeV/c^2 ($I_3^L = \pm1$) are excluded by measurements of Γ_{Z^0}, as indicated by the dotted lines.

Thus it should be possible to neutralize these effects through model engineering (higher dim. contact int.)

Bhabha Scattering

Constrains doubly charged scalars (here $\Delta \equiv H^{--}$) also at lower energies

[Swartz, PRD, 1989]



$$\sigma_{\text{Higgs}}(\cos\theta) \equiv \frac{d\sigma}{d(\cos\theta)}$$

$$= \frac{\pi\alpha^2}{4s}[4A_0 + A_-(1-\cos\theta)^2 + A_+(1+\cos\theta)^2] ,$$

where the coefficients A_0, A_-, and A_+ are defined as

$$A_0 = \left(\frac{s}{t}\right)^2 \left|1+\frac{g_r g_l}{e^2}\frac{t}{t_Z}\right|^2 ,$$

$$A_- = \left|1+\frac{g_r g_l}{e^2}\frac{s}{s_Z}\right|^2 ,$$

$$A_+ = \frac{1}{2}\left|1+\frac{s}{t}+\frac{g_r^2}{e^2}\left(\frac{s}{s_Z}+\frac{s}{t_Z}\right)+\frac{2g_{ee}^2 s}{e^2 M_\Delta^2}\right|^2 + \frac{1}{2}\left|1+\frac{s}{t}+\frac{g_l^2}{e^2}\left(\frac{s}{s_Z}+\frac{s}{t_Z}\right)\right|^2 .$$

Only holds for $M_\Delta^2 \gg s$; otherwise,

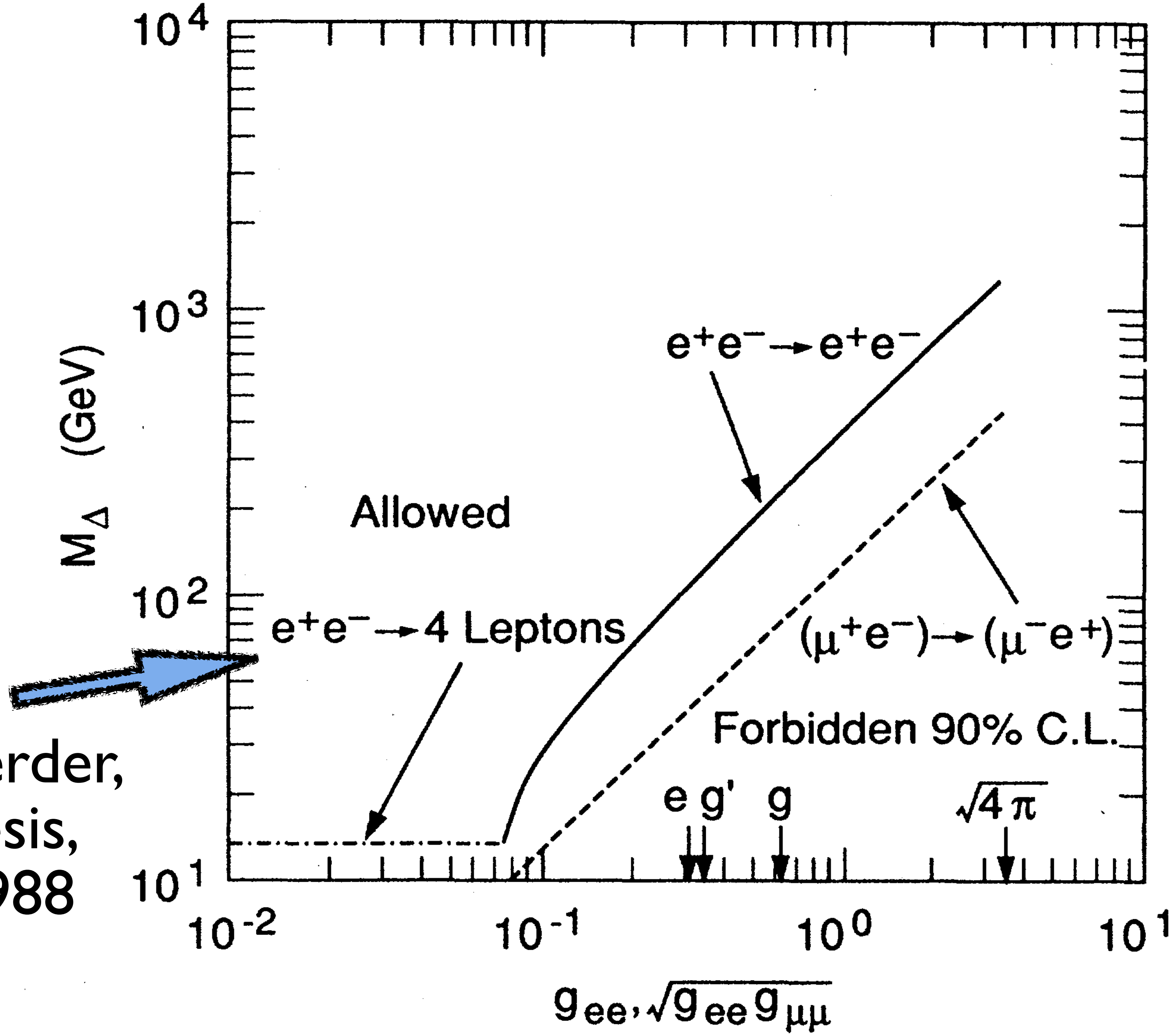
$$M_\Delta^2 \to M_\Delta^2 - t';$$

$$t' = -s(1+\cos\theta)/2$$

Bhabha Scattering

[Swartz, PRD, 1989]

Light doubly-charged singlet X_1 & X_3 possible



Possible after model engineering?

F. LeDiberder, Ph.D. thesis, Orsay, 1988

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) $(g-2)_e$ (superseded by Møller, save for light masses)

Light mass solution to Δa_e puzzle

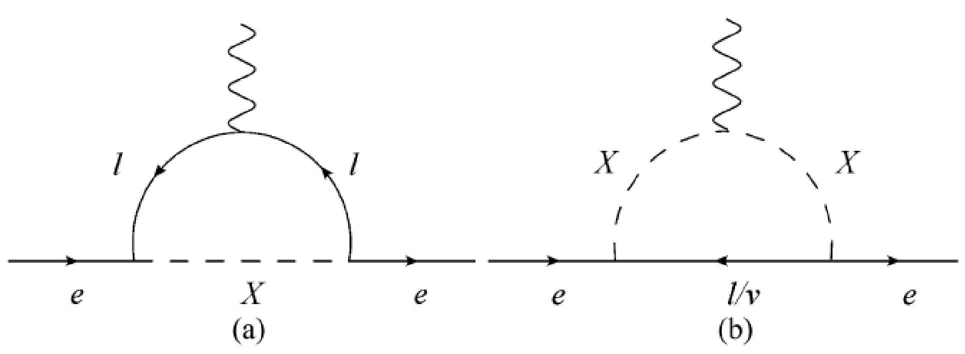
v) Nuclear stability [S.G. & Xinshuai Yan, 1907.12571]

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

vi) $H\bar{H}$ annihilation

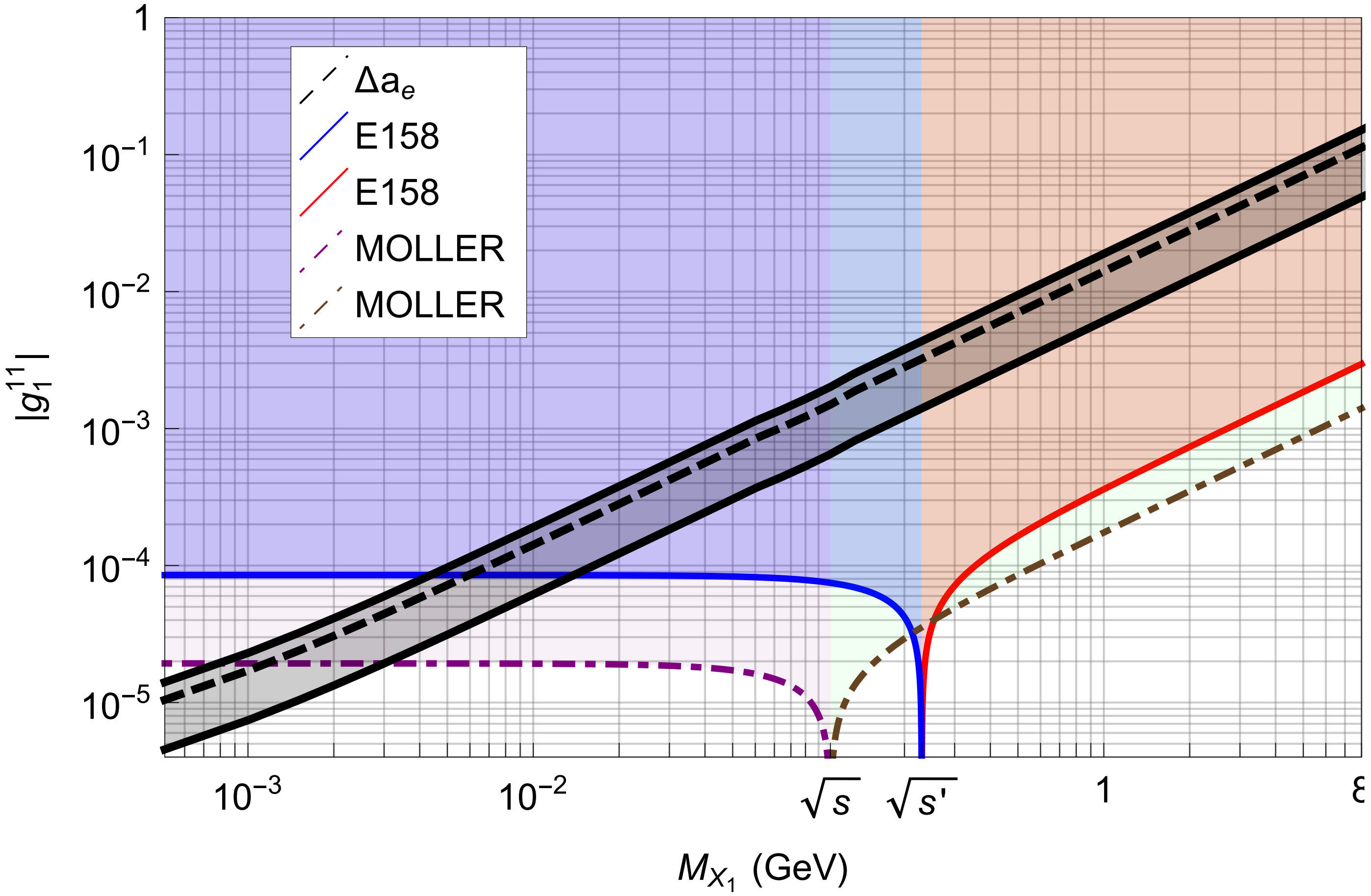
Beware galactic magnetic fields!

vii) H stability



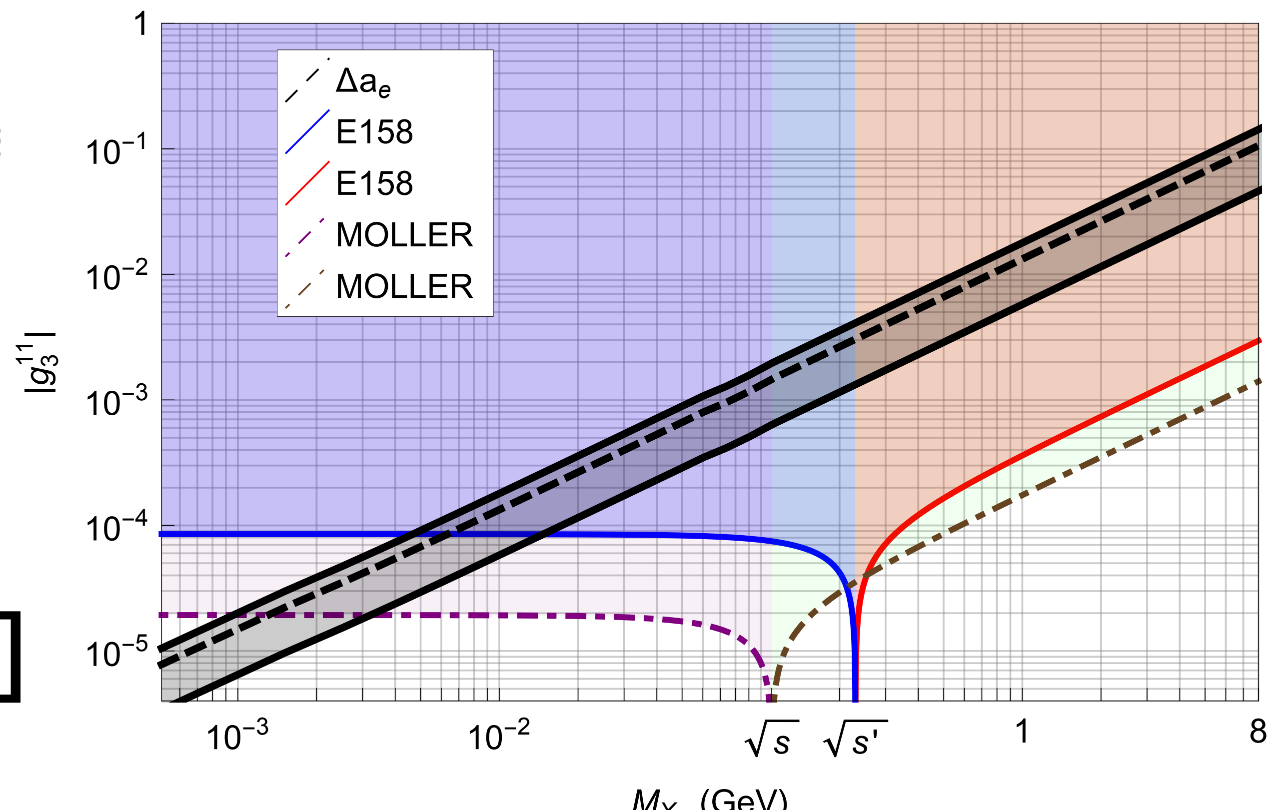
Δa_e Solutions Confront PVES

Doubly Charged Scalars Appear in s-Channel



X_1

X_3

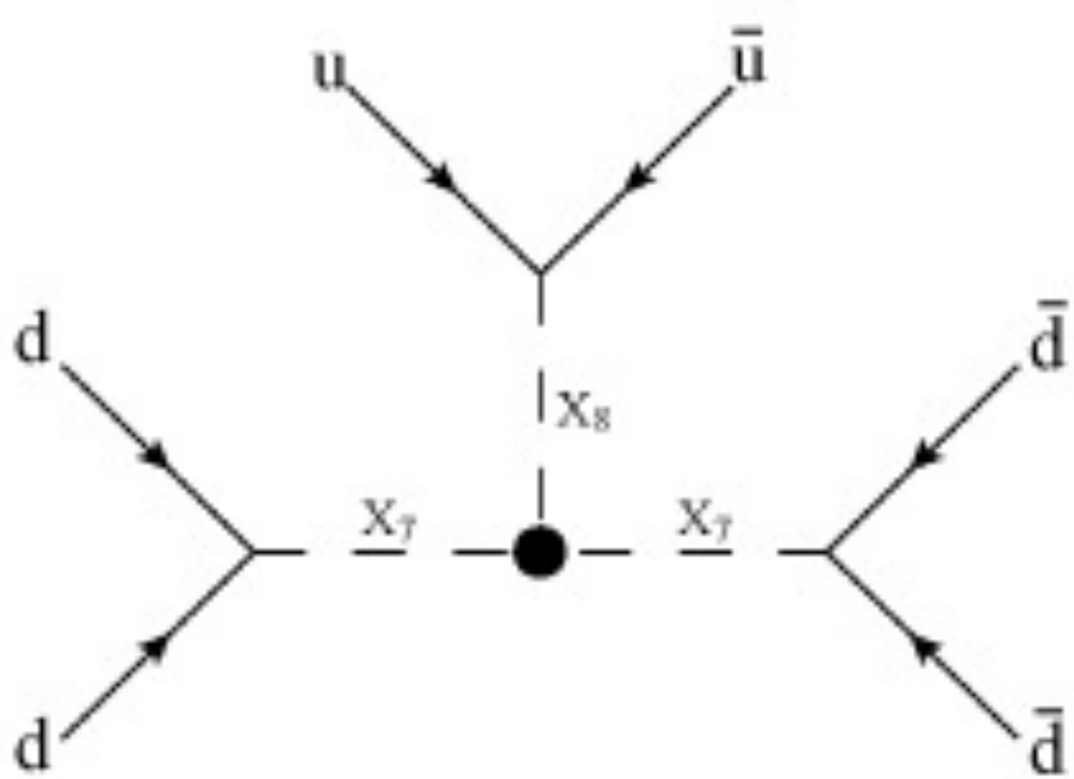


[S.G. & Xinshuai Yan, 1907.12571]

Also subject to (KLOE-2) α running constraint

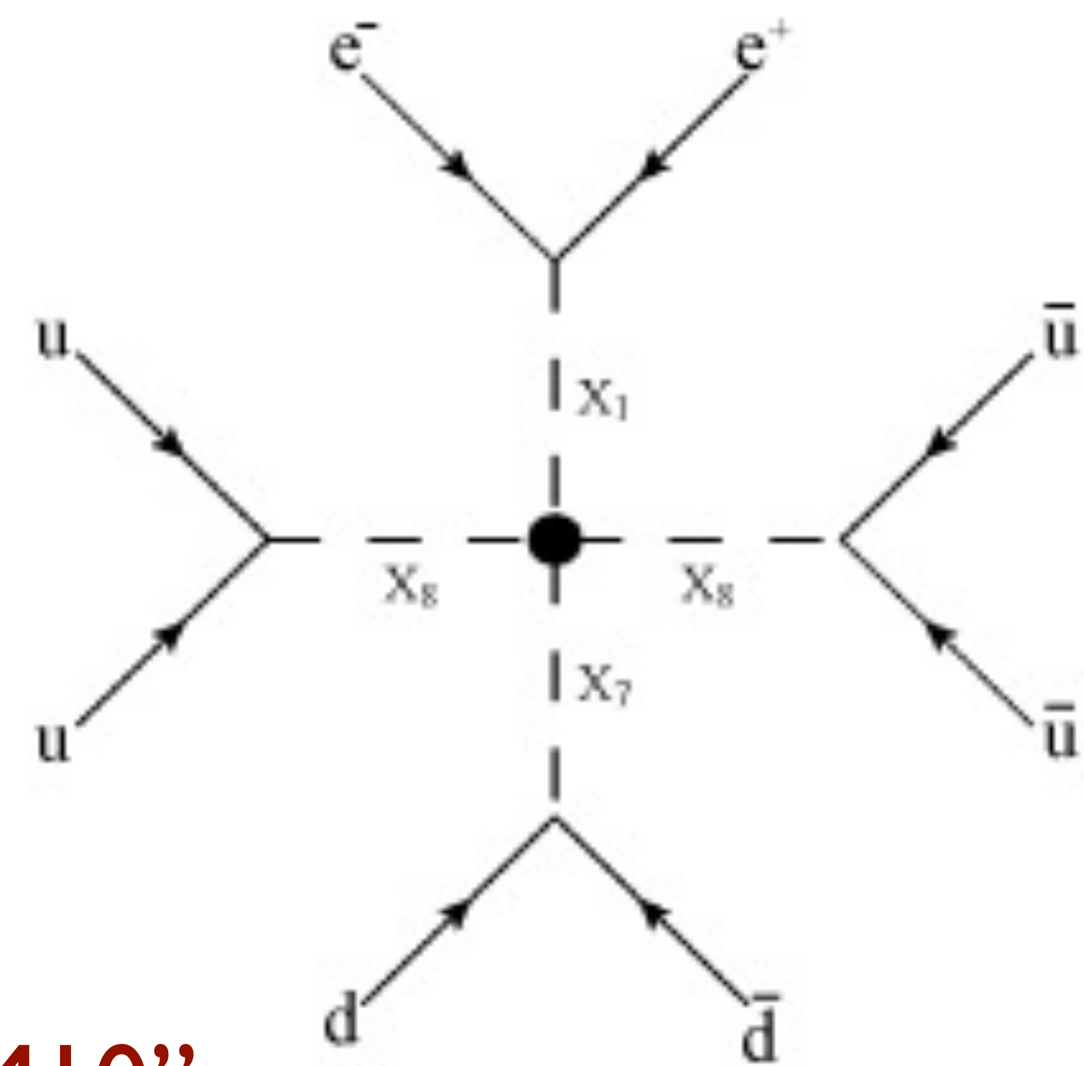
Connecting |ΔB|=2 to |ΔL|=2…

An example…



"M3"

(a)



"M10"

(b)

n-$\bar{n}$

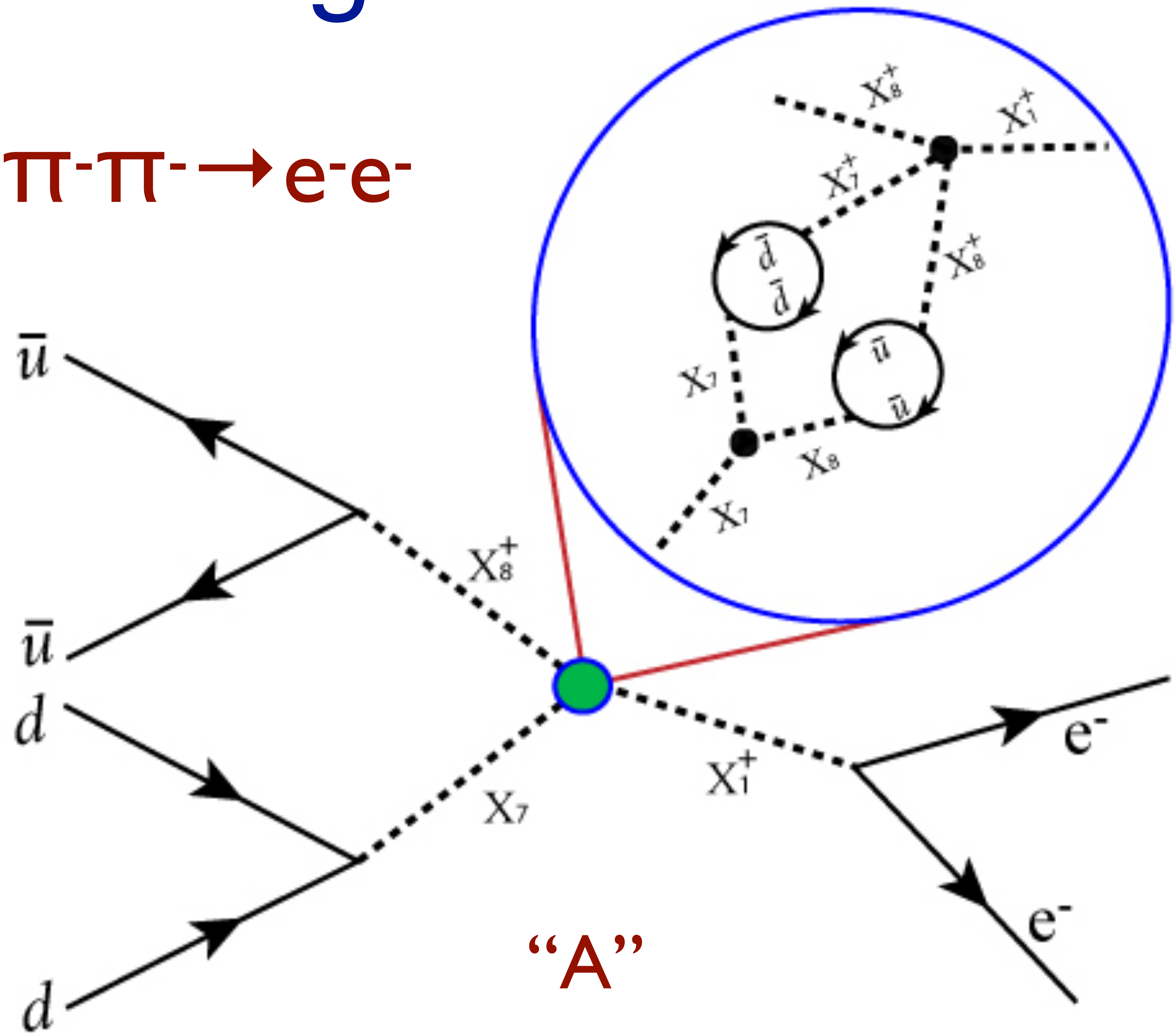
"Oscillation"

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

"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]

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

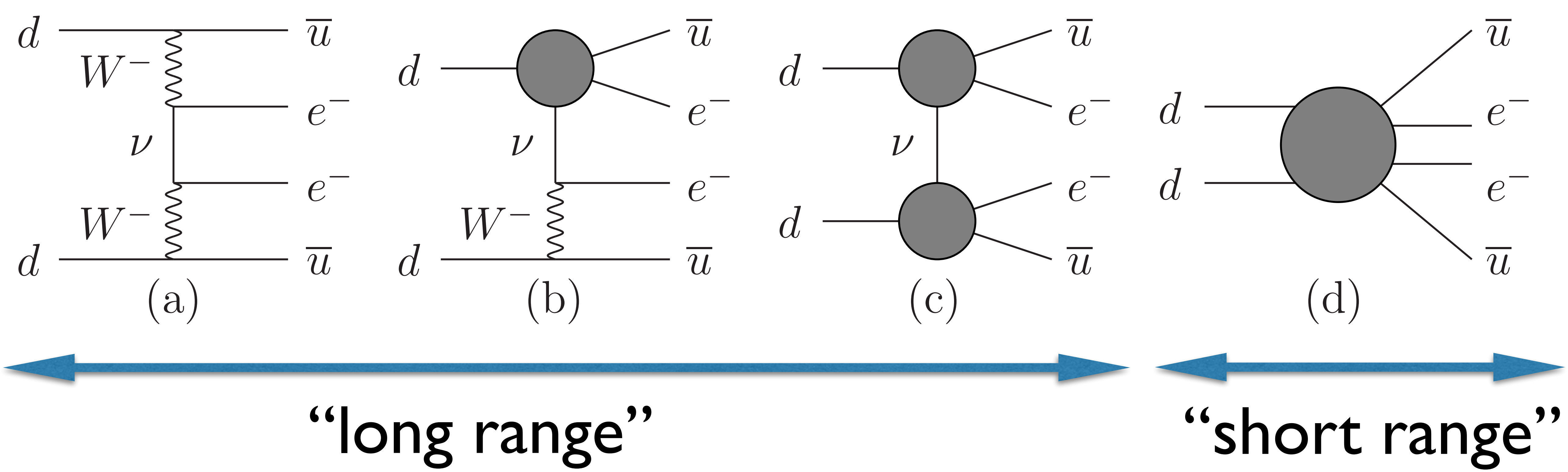
If observed, the ν has a Majorana mass

[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"



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

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

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**]

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

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

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

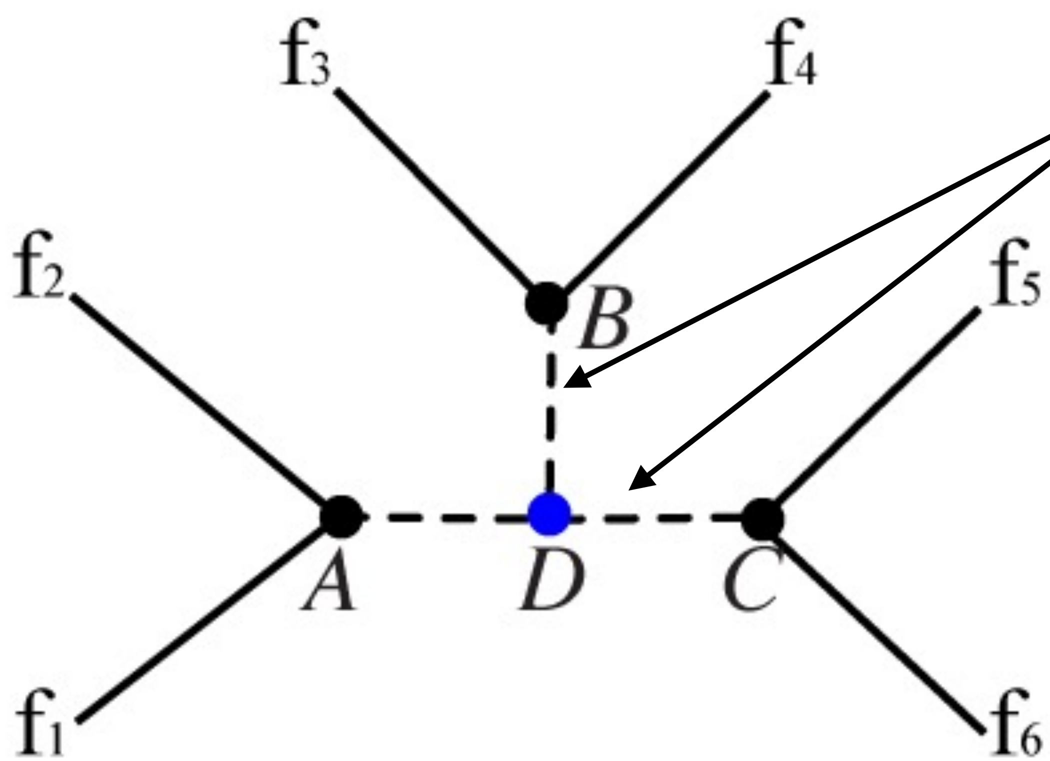
n-$\bar{n}$ $\qquad$ $\pi^-\pi^- \to e^-e^-$

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

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]

A New Interpretation of Δa_e

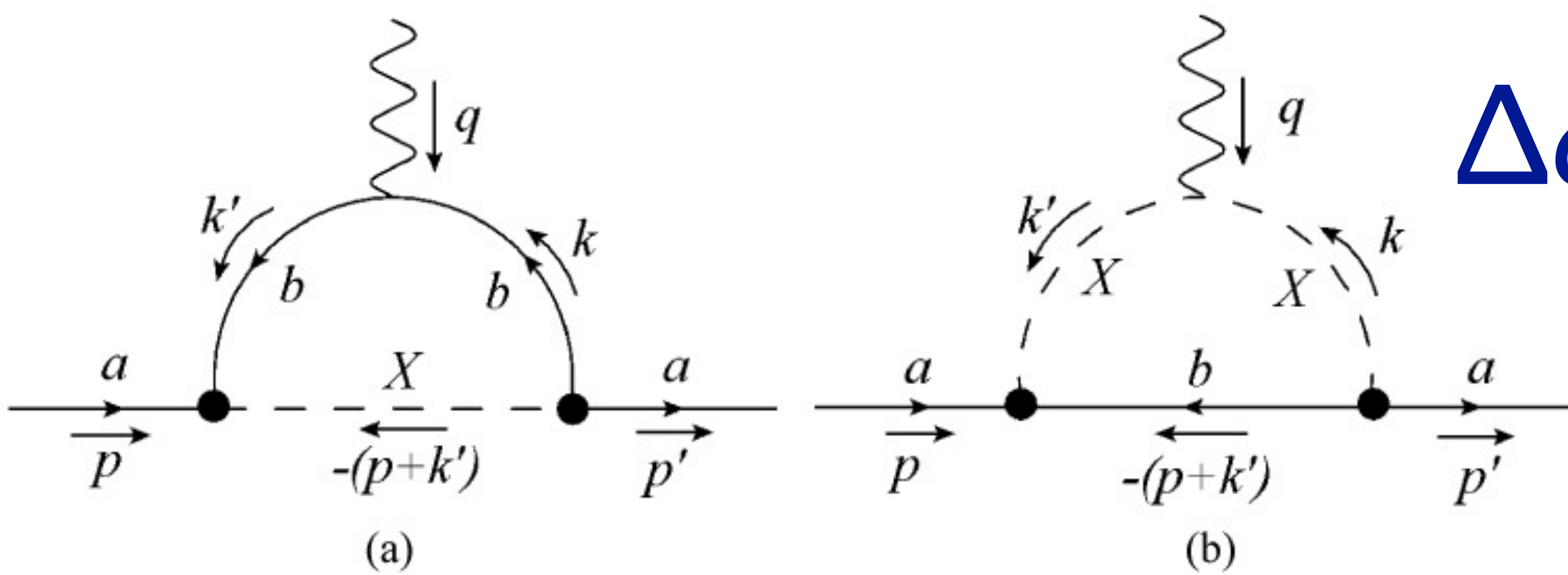
Enter Lepton-Number-Carrying Scalars

[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

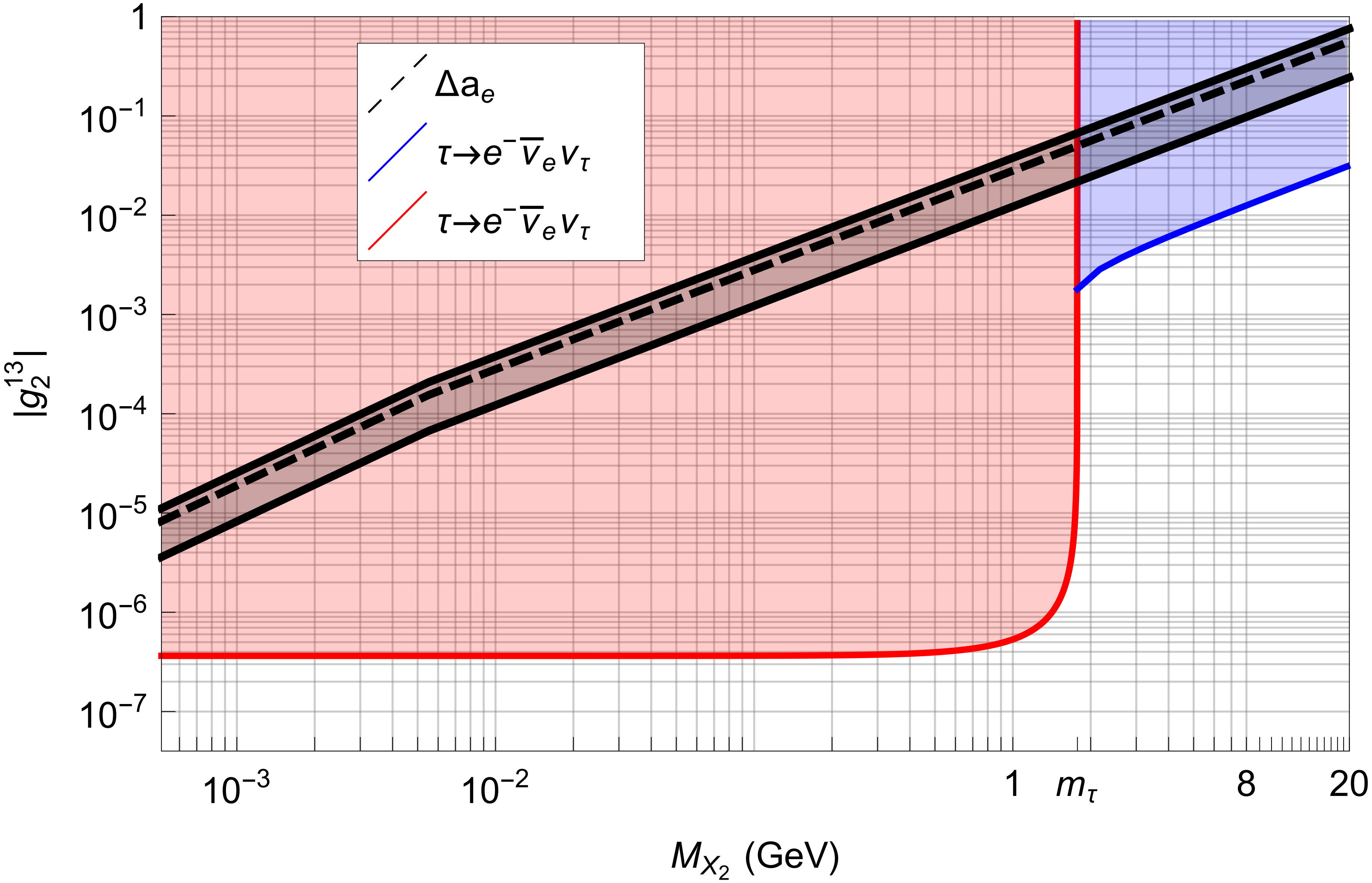
No "secret ingredients"!



$\Delta a_e < 0!$

Δa_e Solutions Confront τ Decay

Scalar X_2 cannot explain the anomaly



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