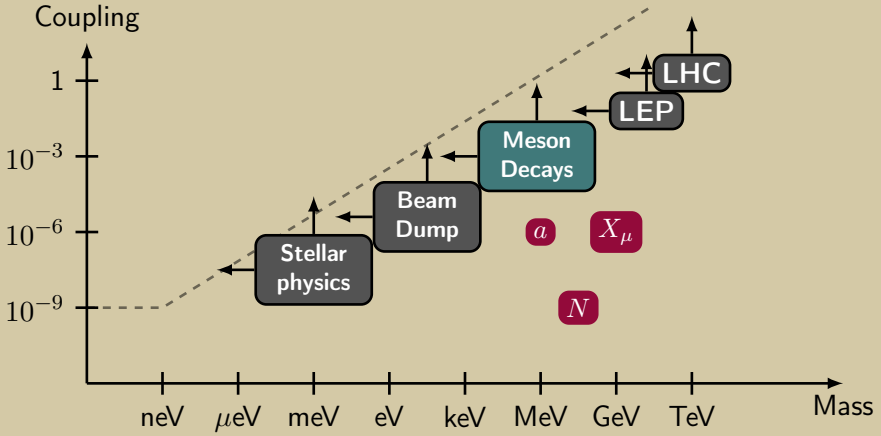
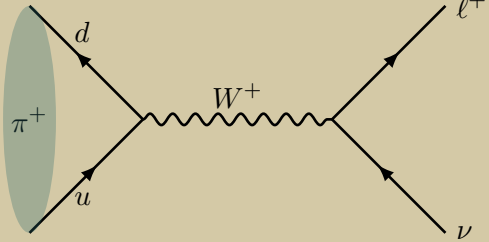
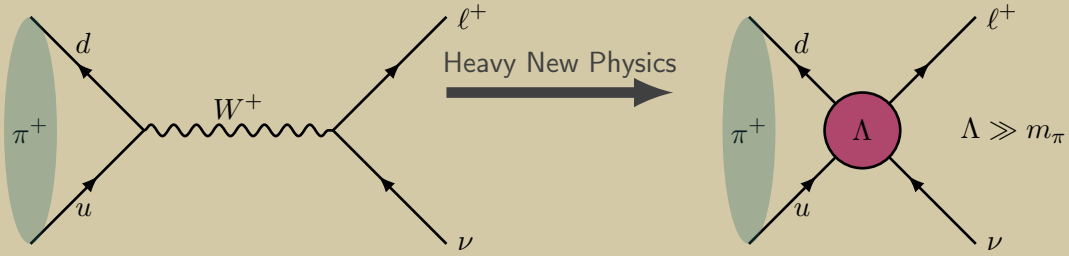
Meson decays as probes of light new physics

Jeff Dror




d
π^+
u
W^+
ℓ^+
ν


π^+
d
u
W^+
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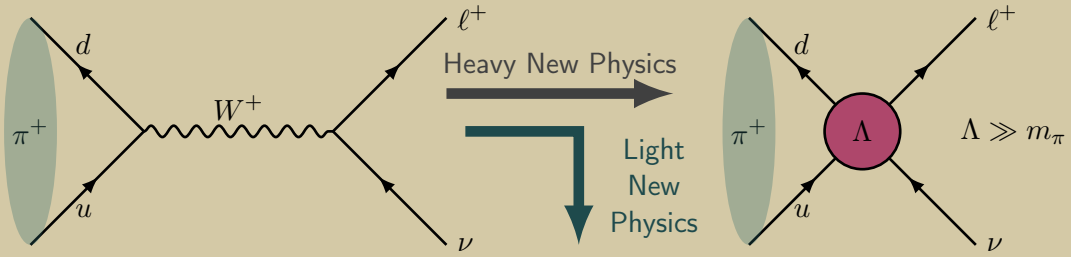
Heavy New Physics
π^+
d
u
Λ
ℓ^+
ν
$\Lambda \gg m_\pi$


d
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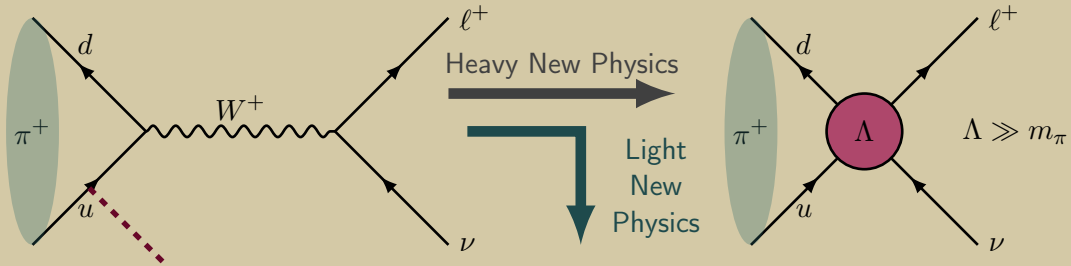
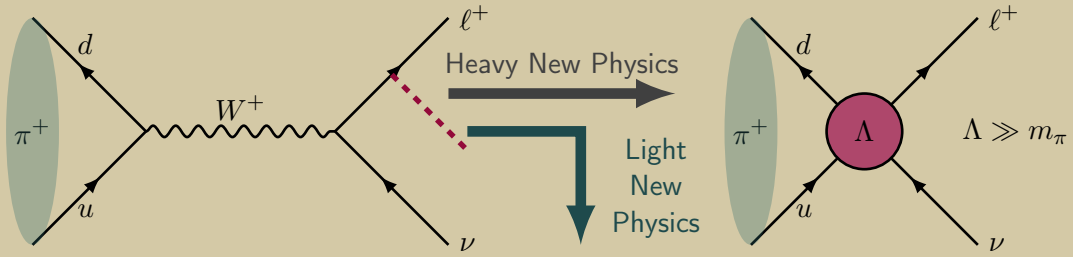


Spin	Coupling	Decay Modes
0	u, d	e^+e^-
1/2	W^+	$\gamma\gamma$
1	ℓ^+	$\nu\nu$
	ν	$e^+e^-\nu$



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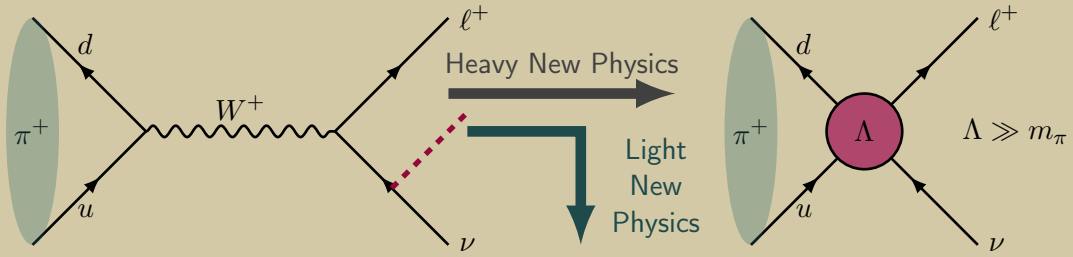

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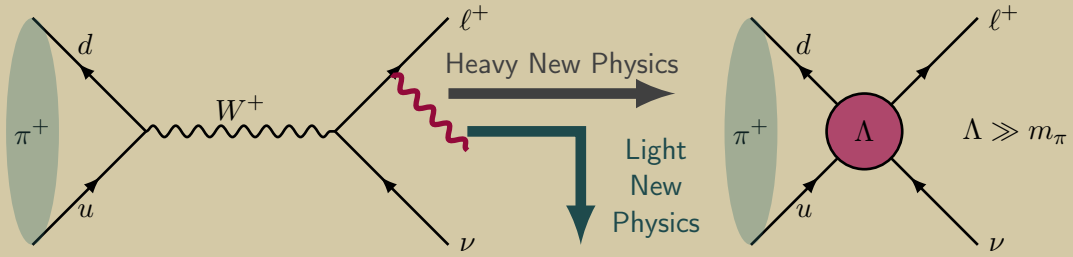

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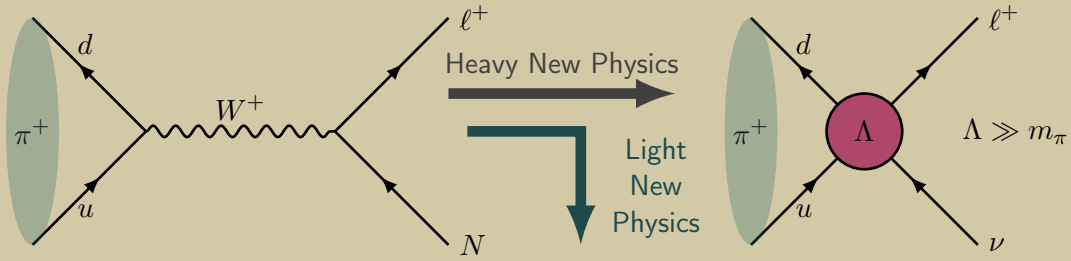

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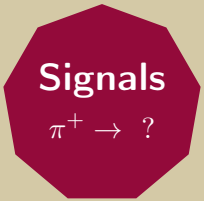
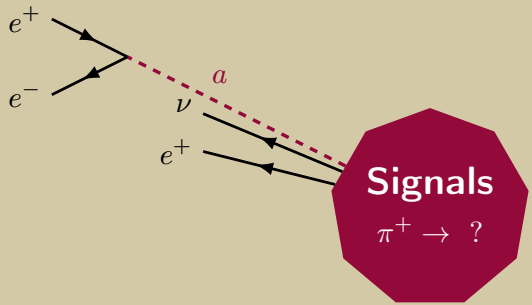
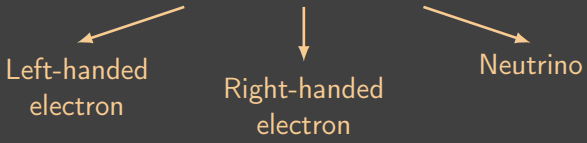

Signals
$\pi^+ \to\ ?$

Axion



Leptophilic ALPs



ALL leptons are interesting
(focus on electrons)

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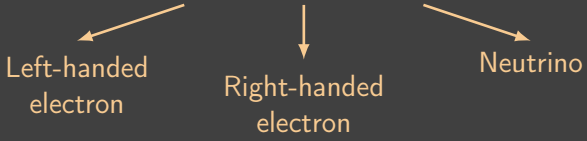

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Electroweak invariance unifies left-handed electron and neutrino

Leptophilic ALPs

Left-handed electron

Right-handed electron

Neutrino

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Electroweak invariance unifies left-handed electron and neutrino

$$\frac{g_{eL}}{m_e}\partial_\mu a \bar{L}\gamma^\mu L + \frac{g_{eR}}{m_e}\partial_\mu a \bar{e}_R \gamma^\mu e_R$$

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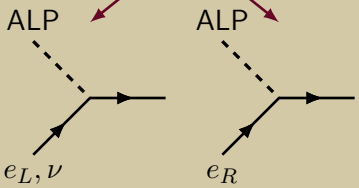

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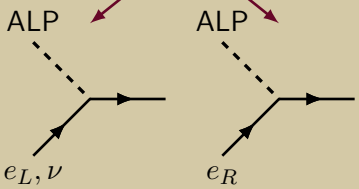

Electroweak symmetry is broken anyways...

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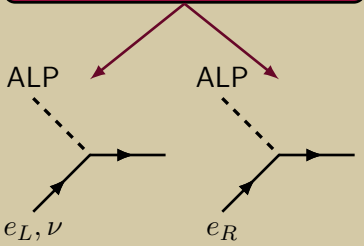

Electroweak symmetry is broken anyways...

$$\frac{g_{eL}}{m_e}\partial_\mu a \bar{e}_L \gamma^\mu e_L + \frac{g_{\nu L}}{m_e}\partial_\mu a \bar{\nu}_L \gamma^\mu \nu_L + \frac{g_{eR}}{m_e}\partial_\mu a \bar{e}_R \gamma^\mu e_R$$

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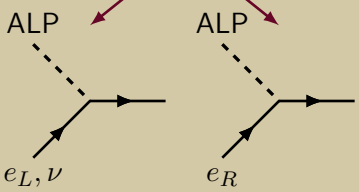

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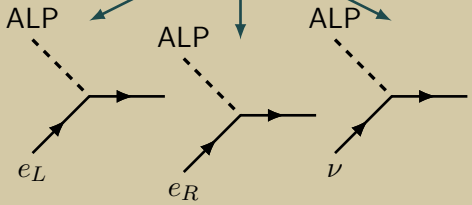

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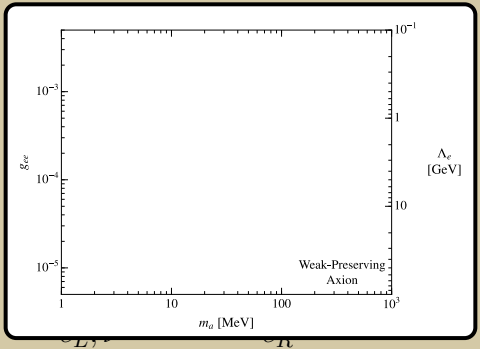

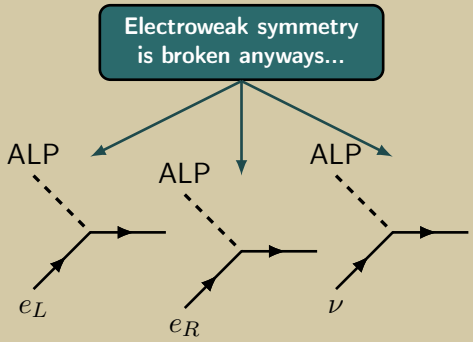

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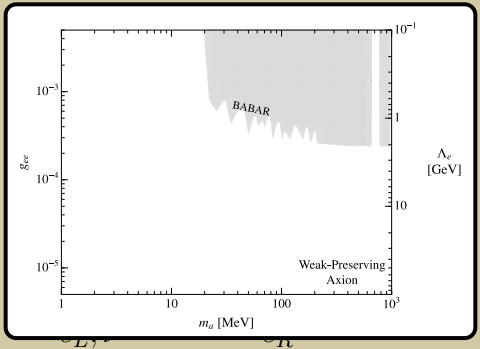

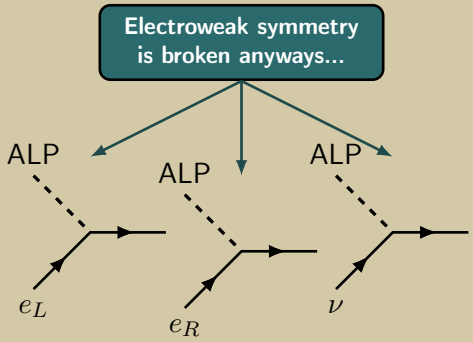

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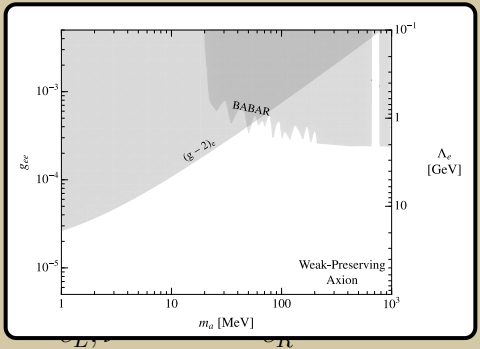

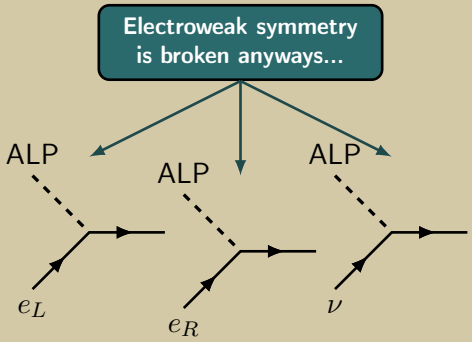

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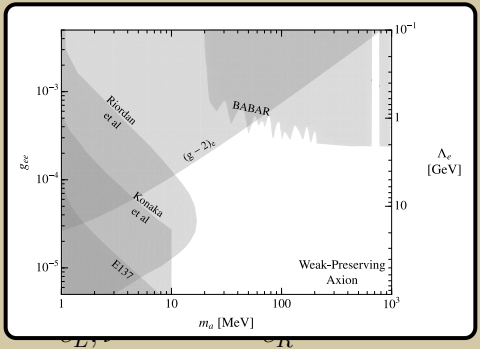

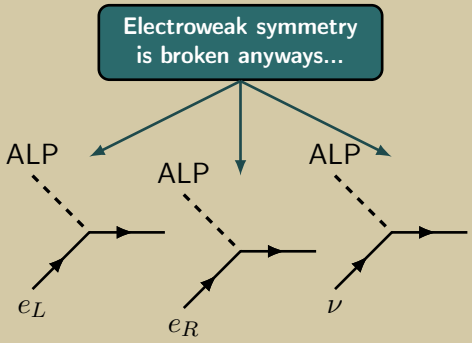

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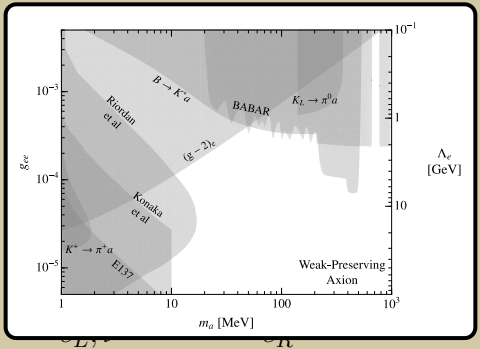

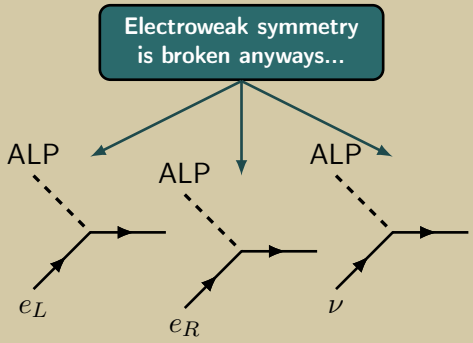

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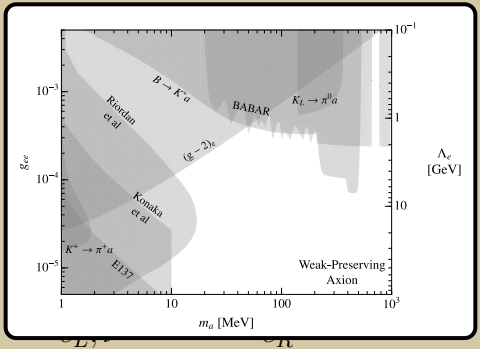
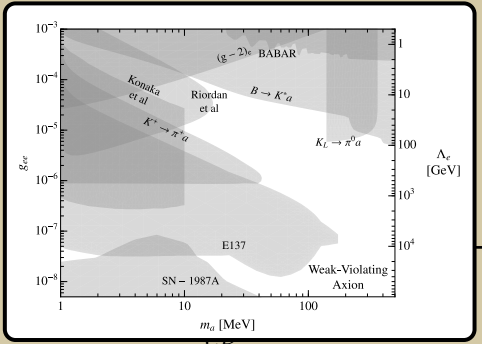
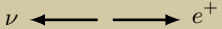




ALPs from π^+ decay*

↳ ALP removes helicity suppression



*ALP-π^0 mixing and quark coupling

E.g., [**Krauss, Wise** - '86], [**Bardeen et al** - '87], [**Altmannshofer et al** - 19]

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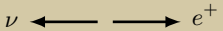

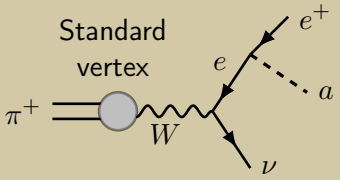

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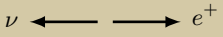

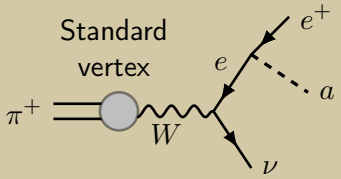

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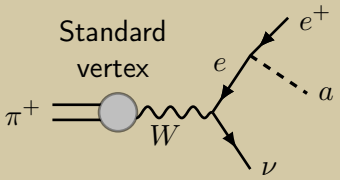
Weak-preserving

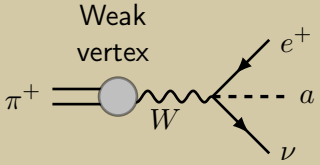
$$\Gamma_{\pi^+ \to e^+ \nu a} \propto g_{ee}^2 \frac{m_\pi^2 f_{\pi^+}^2}{m_W^4}$$

$$\mathrm{Br}(\pi^+ \to e^+ \nu a) \simeq 1.0 \times 10^{-8} \left(\frac{g_{ee}}{10^{-3}} \right)^2$$

↳ ALP removes helicity suppression

$\nu \longleftarrow \longrightarrow e^+$





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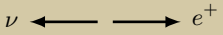

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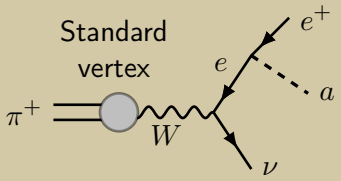
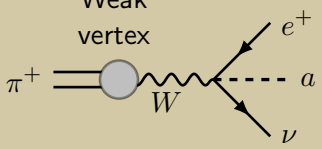


Weak-violating

$$\Gamma_{\pi^+\to e^+\nu a} \propto \frac{g_{ee}^2 m_\pi^2}{m_e^2}\frac{f_{\pi^+}^2 m_\pi^2}{m_W^4}$$

$$\mathrm{Br}(\pi^+ \to e^+\nu a) \simeq 4.5\times 10^{-5}\left(\frac{g_{ee}}{10^{-3}}\right)^2$$



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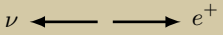

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Detectable

Weak-violating

$$\Gamma_{\pi^+\to e^+\nu a} \propto \frac{g_{ee}^2 m_\pi^2}{m_e^2}\frac{f_{\pi^+}^2 m_\pi^2}{m_W^4}$$

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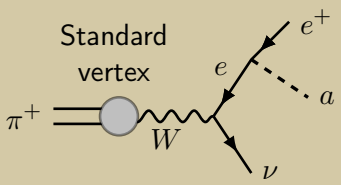
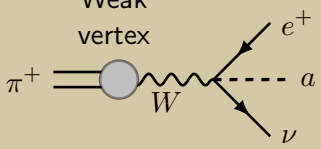
Standard vertex



Weak vertex



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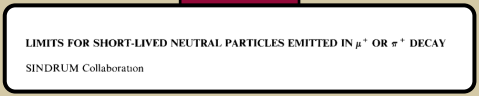
Experimental Capabilities

Experimental Capabilities

Past

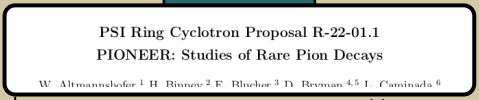


LIMITS FOR SHORT-LIVED NEUTRAL PARTICLES EMITTED IN μ^+ OR π^+ DECAY

SINDRUM Collaboration

↳ Reached $\mathrm{Br}_{\pi^+ \to e^+ \nu a} \lesssim 10^{-10}$

Future



PSI Ring Cyclotron Proposal R-22-01.1

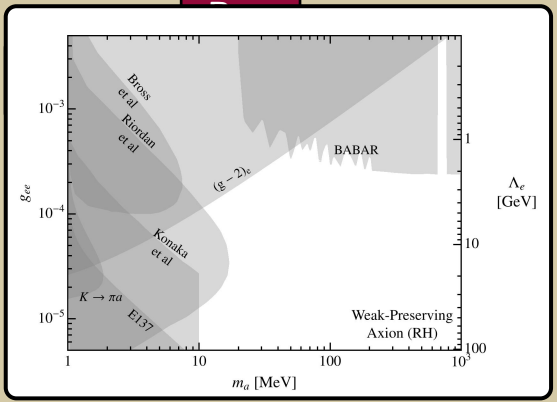
PIONEER: Studies of Rare Pion Decays

W. Altmannshofer [1] H. Binney [2] E. Blucher [3] D. Bryman [4,5] L. Caminada [6]

↳ Reach $\mathrm{Br}_{\pi^+ \to e^+ \nu a} \lesssim 10^{-11}$?

Experimental Capabilities

Altmannshofer, JD, Gori '22



Future

PSI Ring Cyclotron Proposal R-22-01.1
PIONEER: Studies of Rare Pion Decays
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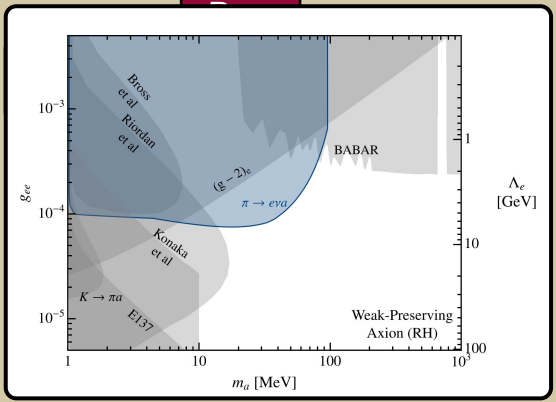

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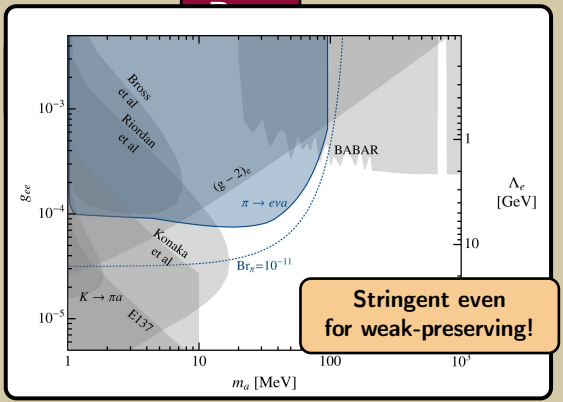

Stringent even for weak-preserving!

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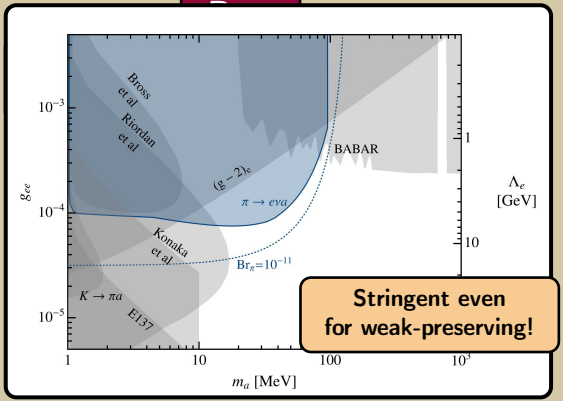

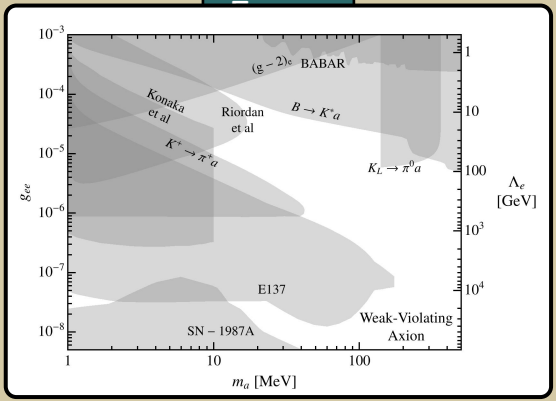

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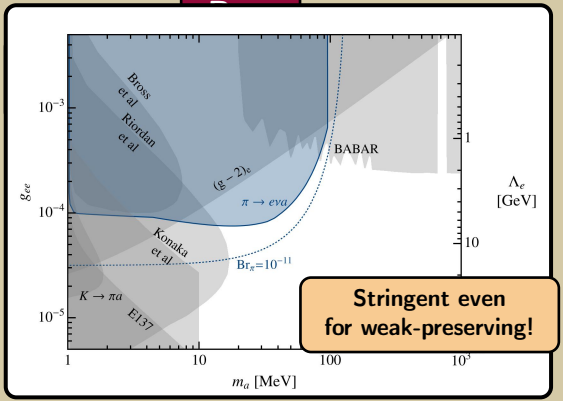

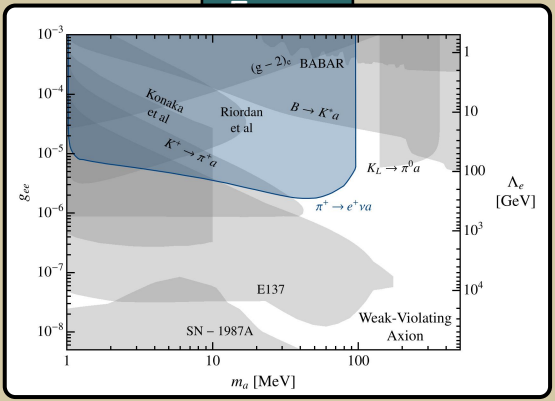

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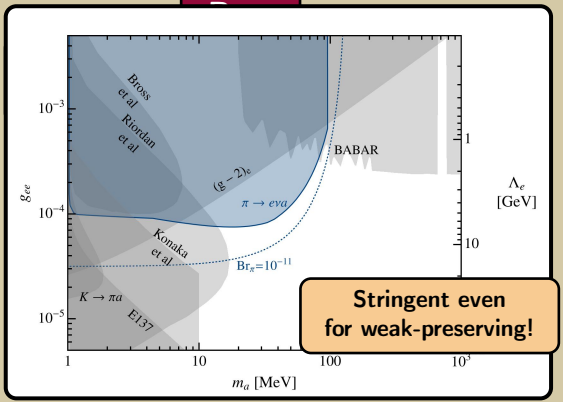

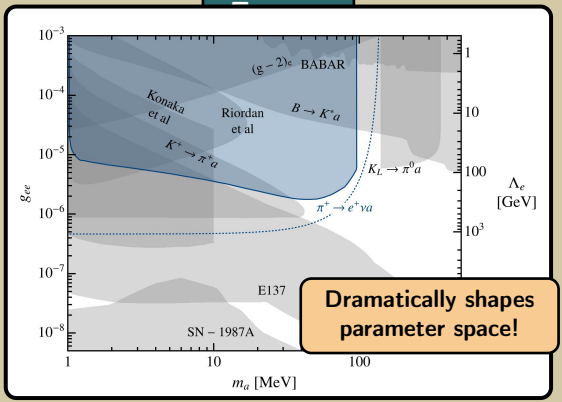

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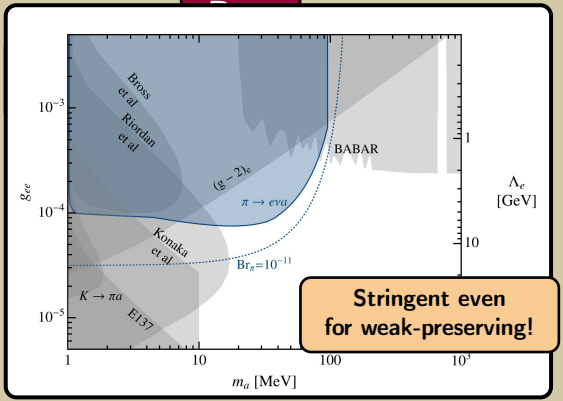
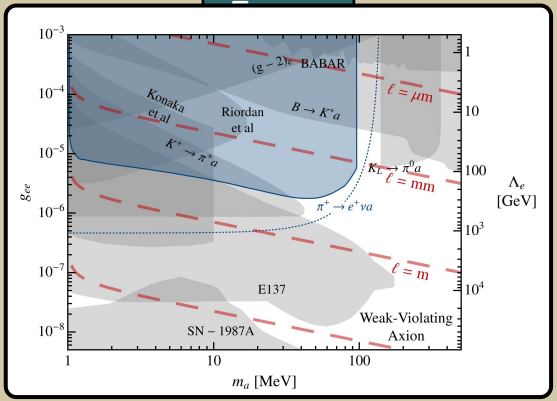
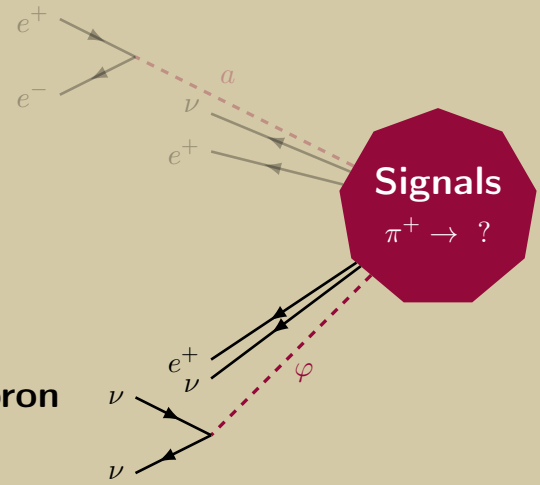
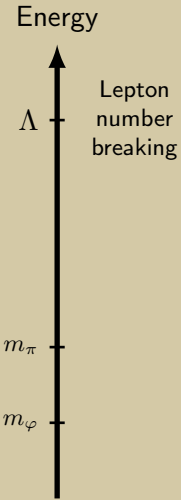




Axion



The Majoran



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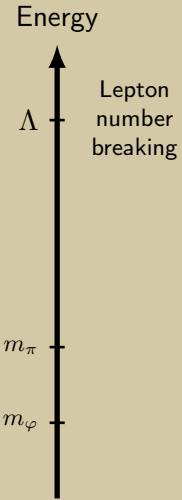
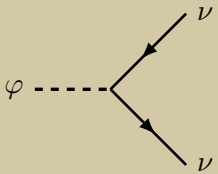


$$\mathcal{L} = \frac{m_\nu}{\Lambda}\varphi\nu\nu$$



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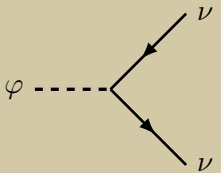
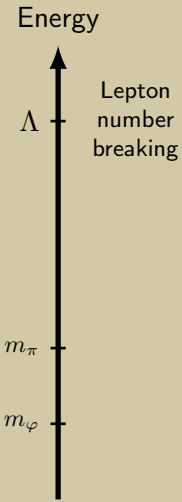


$\pi^+ \to e^+\nu(\varphi \to \nu\nu)$ competes with $0\nu2\beta$, SN 1987A

Barger, Keung, Pakvasa '82

The Majoran



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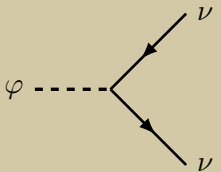

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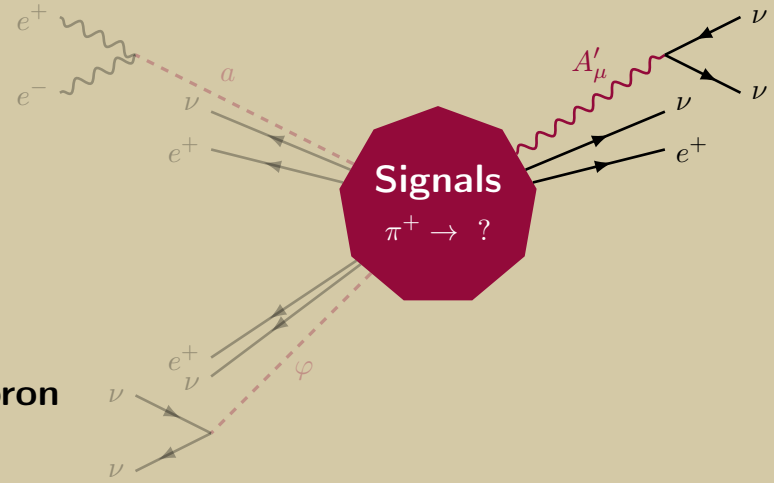
$$\frac{\Gamma(\pi^+ \to e^+\nu\varphi)/\Gamma(\pi^+ \to \mu^+\nu\varphi)}{\Gamma(\pi^+ \to e^+\nu)/\Gamma(\pi^+ \to \mu^+\nu)} < 1.0014 \quad \Rightarrow \quad \frac{m_\nu}{\Lambda} < 0.003$$

PIENU '21

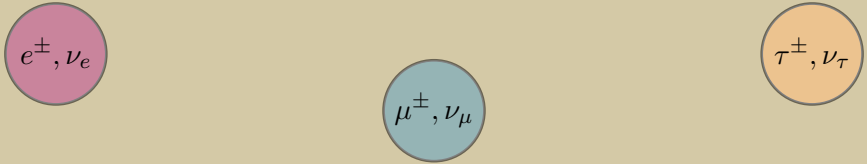
Axion

Gauge boson



Majoron

Leptophilic Gauge Symmetries



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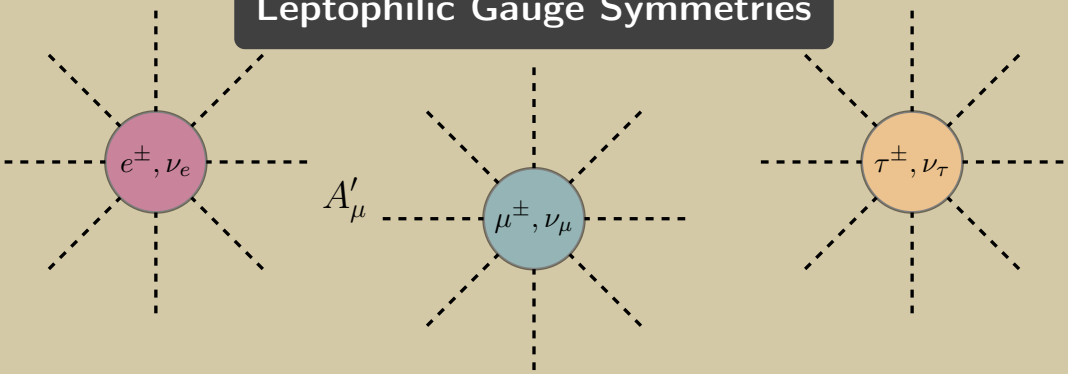

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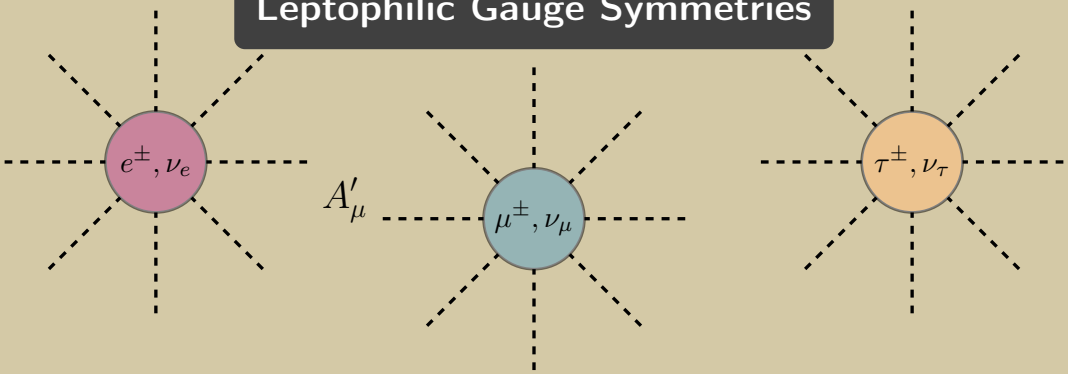

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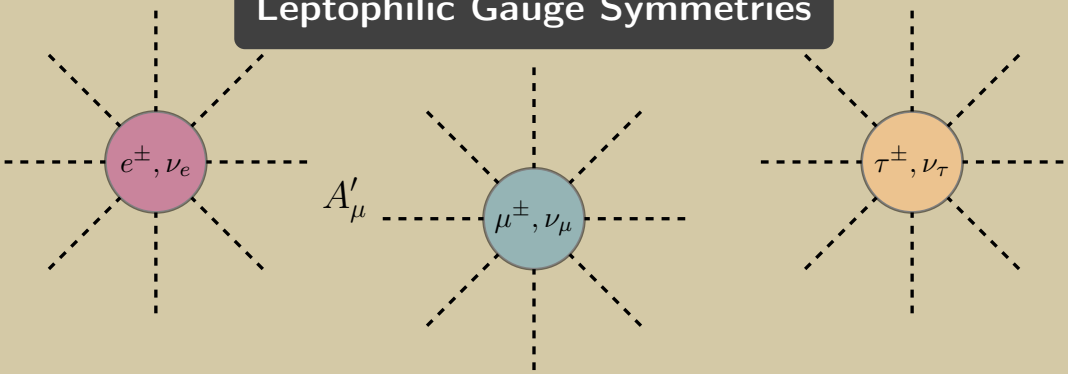

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Surprising Fact: → JD '20 → **Ultralight** $A'_\mu \sim \varphi$

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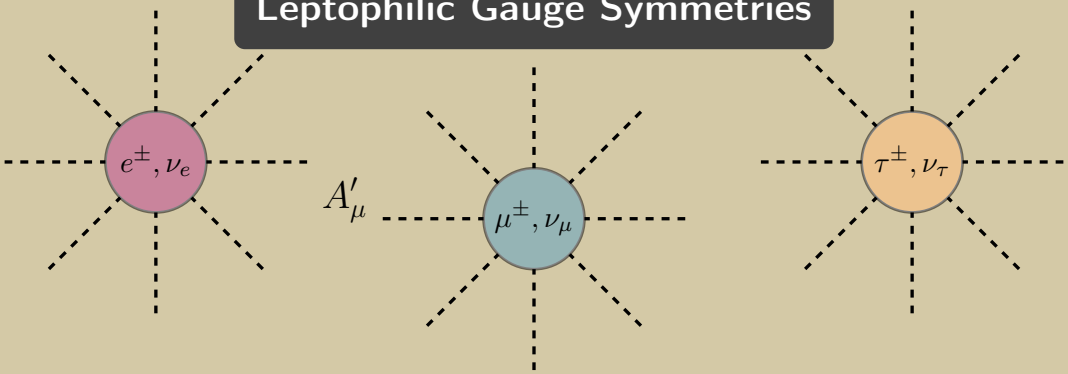

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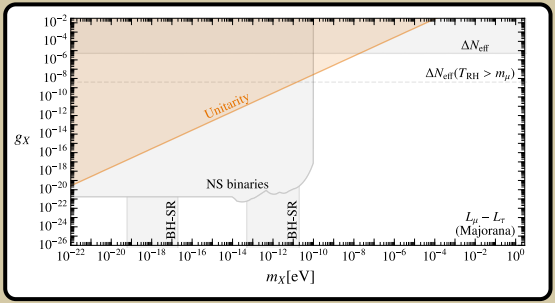
Surprising Fact: → JD '20 → **Ultralight** $A'_\mu \sim \varphi$

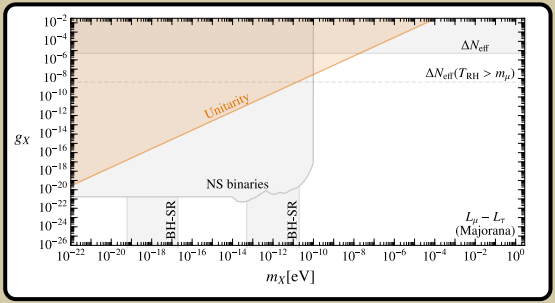
$L_i - L_j$ through $\pi^+ \to e^+ \nu a$ decay



$L_i - L_j$ through $\pi^+ \to e^+ \nu a$ decay

↳ Need invisible search

$$\frac{g_X m_\nu}{m_{A'}} < 0.003$$ PIENU '21



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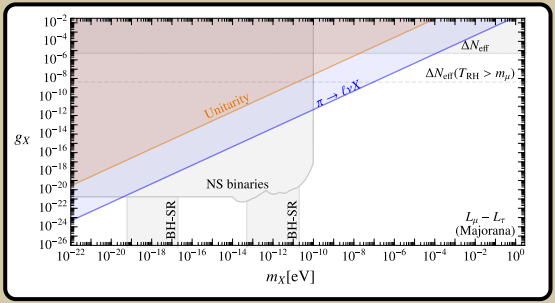

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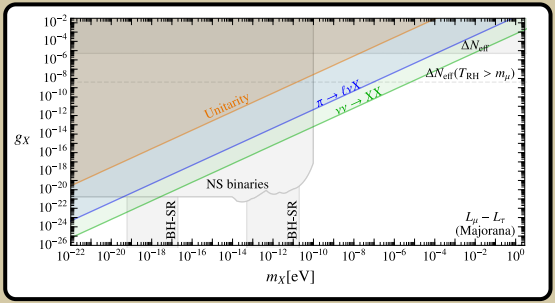

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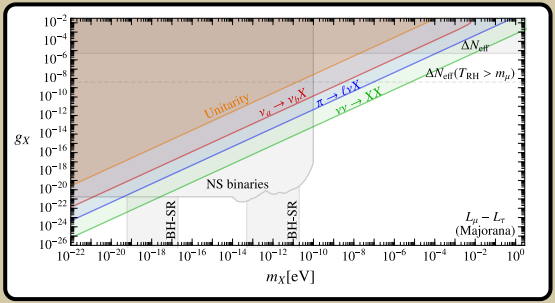

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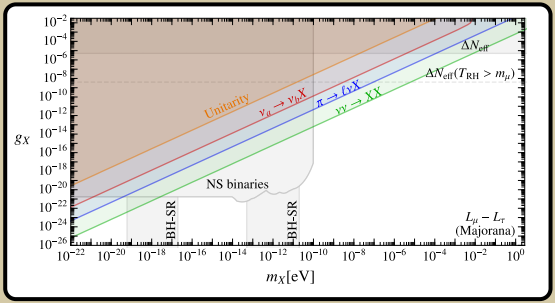

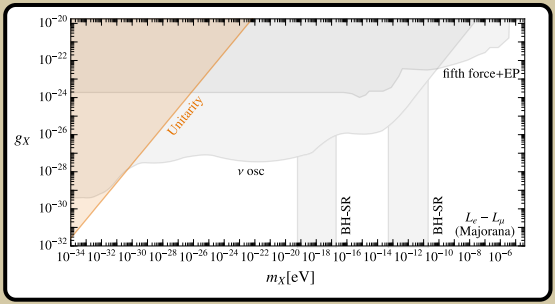

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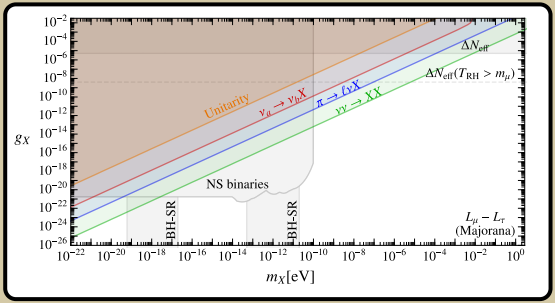

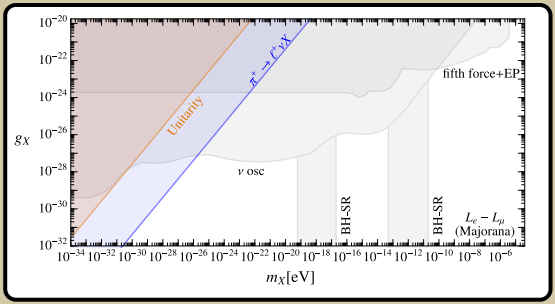

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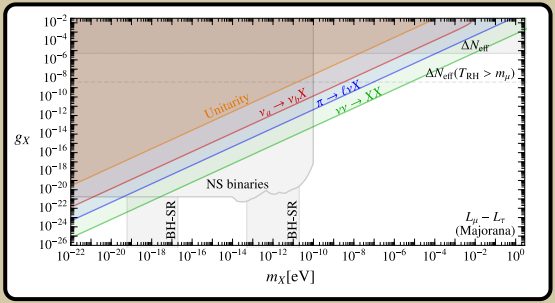

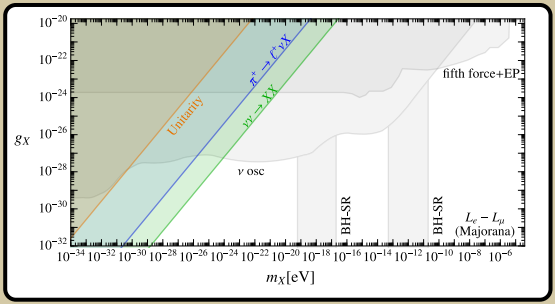

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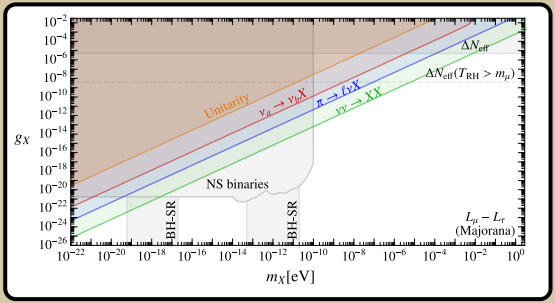
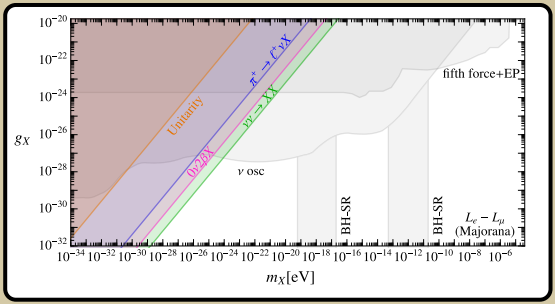
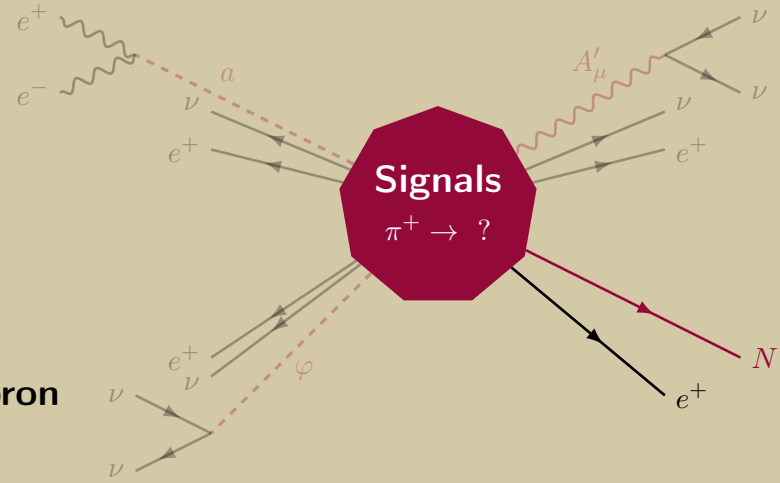




Axion

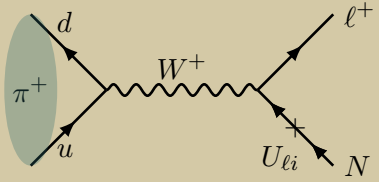
Gauge boson

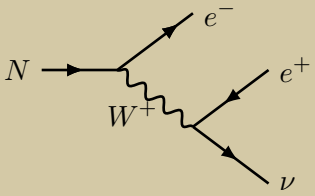


Majoron

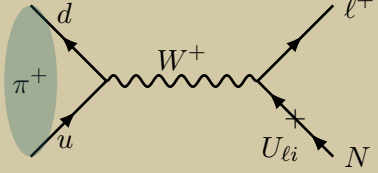
Sterile neutrinos

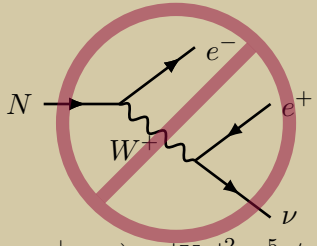
Sterile Neutrinos





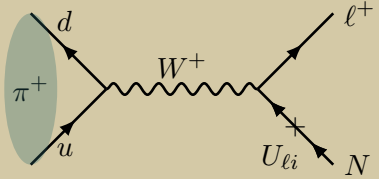
Sterile Neutrinos

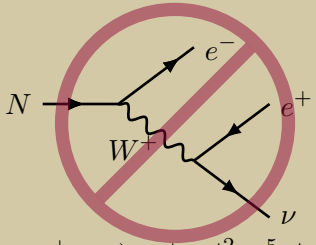




$$\Gamma(N \to e^+ e^- \nu) \propto |U_{\ell i}|^2 \, m_N^5 / m_W^4$$

Sterile Neutrinos





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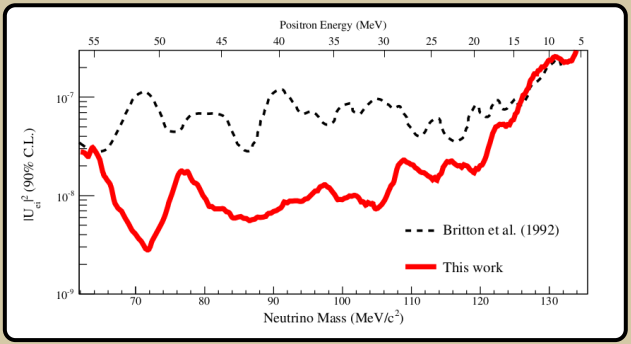
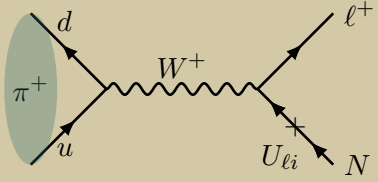
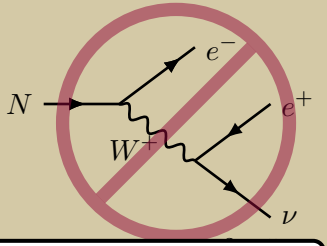
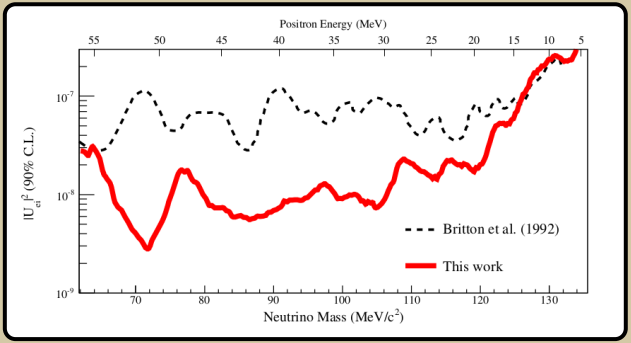


PIENU '21

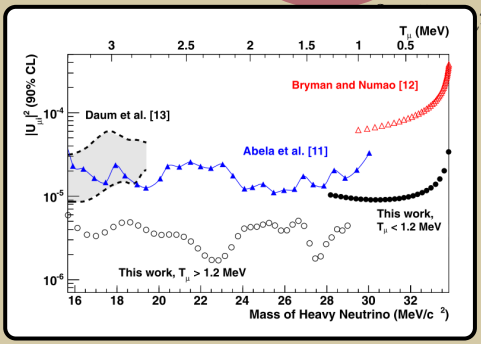
Sterile Neutrinos







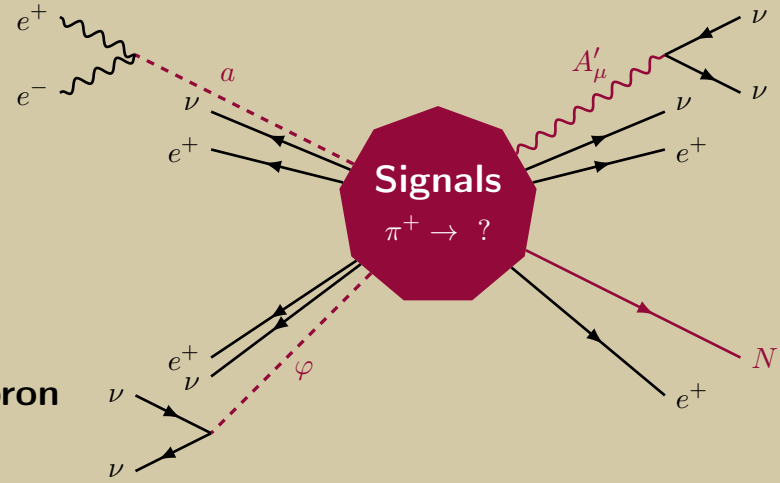
PIENU '21



PIENU '19

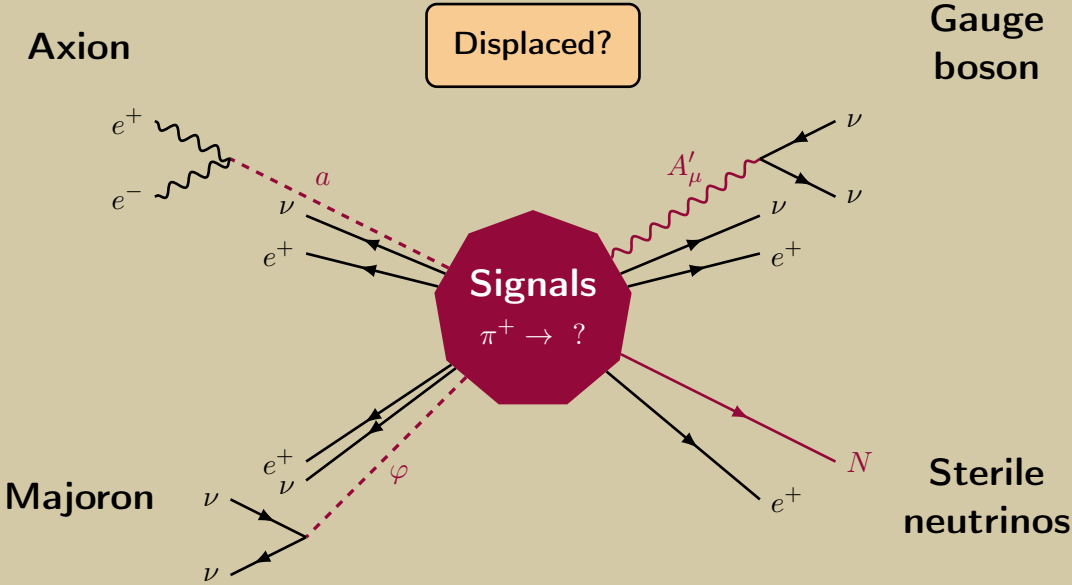
Axion

Gauge boson



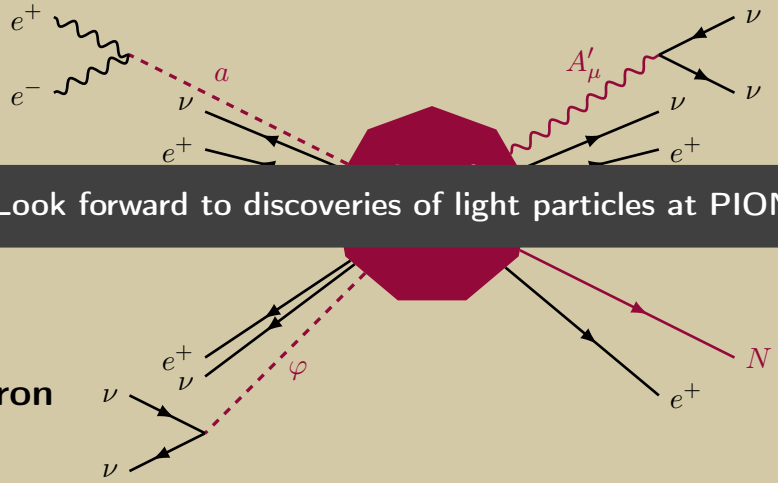
Majoron

Sterile neutrinos


Axion
Displaced?
Gauge boson
e^+
e^-
a
ν
e^+
Signals
$\pi^+ \to$?
A'_μ
ν
ν
ν
e^+
Majoron
e^+
ν
φ
ν
ν
N
e^+
Sterile neutrinos

Axion

Gauge boson



Look forward to discoveries of light particles at PIONEER!

Majoron

Sterile neutrinos