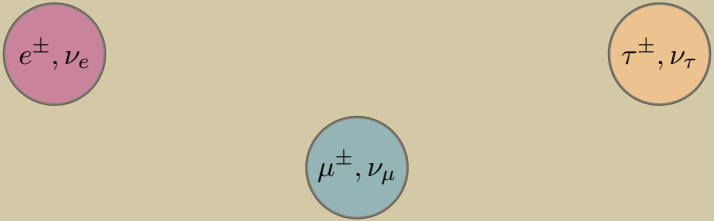
New Insights Into Axion-Lepton Interactions

Network for Neutrinos, Nuclear Astrophysics, and Symmetries Seminar

[2209.00665] Altmannshofer, JD, and Gori

Jeff Dror

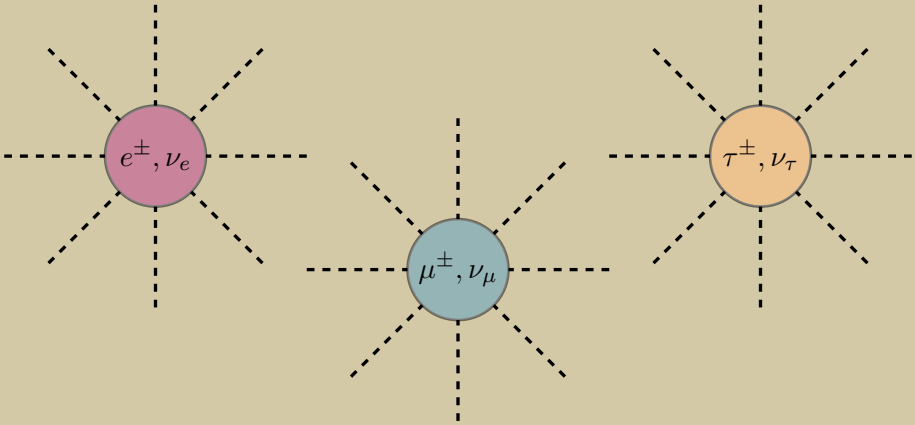


New Insights Into Axion-Lepton Interactions

Network for Neutrinos, Nuclear Astrophysics, and Symmetries Seminar

[2209.00665] Altmannshofer, JD, and Gori

Jeff Dror



Outline

Introduction to Lepton-Axion Interactions

Lagrangian reformulation

New set of detection strategies

Implications

Outline

Introduction to Lepton-Axion Interactions

Lagrangian reformulation

New set of detection strategies

Implications

Outline

Introduction to Lepton-Axion Interactions

Lagrangian reformulation

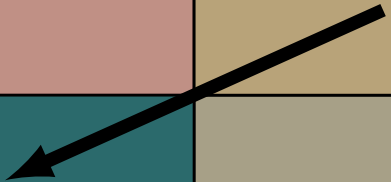
New set of detection strategies

Implications

Outline

Introduction to Lepton-Axion Interactions

Lagrangian reformulation



New set of detection strategies

Implications

Outline

Introduction to Lepton-Axion Interactions

Lagrangian reformulation

New set of detection strategies

Implications

Leptophilic Effective Theory

Shift symmetry:

$$\mathcal{L} = \partial_\mu a \; j^\mu_{\rm PQ}$$

Leptophilic Effective Theory

Shift symmetry:

$$\mathcal{L} = \partial_\mu a \; j^\mu_{\rm PQ}$$

$$j^\mu_{\rm PQ} = \frac{1}{2m_\ell}\left(\bar{g}_{\ell\ell}\bar{\ell}\gamma^\mu\ell + g_{\ell\ell}\bar{\ell}\gamma^\mu\gamma_5\ell + g_{\nu_\ell}\bar{\nu}_\ell\gamma^\mu P_L\nu_\ell\right)$$

- Convenient normalization
- Vector coupling
- Axial-vector coupling
- Neutrino coupling

Leptophilic Effective Theory

Shift symmetry: $\mathcal{L} = \partial_\mu a \; j^\mu_{\rm PQ}$

$$j^\mu_{\rm PQ} = \frac{1}{2m_\ell}\left(\bar{g}_{\ell\ell}\bar{\ell}\gamma^\mu\ell + g_{\ell\ell}\bar{\ell}\gamma^\mu\gamma_5\ell + g_{\nu_\ell}\bar{\nu}_\ell\gamma^\mu P_L\nu_\ell\right)$$

- Convenient normalization
- Vector coupling
- Axial-vector coupling
- Neutrino coupling

Claims in the literature

"The vector coupling is unphysical"

"The neutrino coupling is suppressed by m_ν"

"$\frac{1}{2m_e}\partial_\mu a\bar{e}\gamma^\mu\gamma_5 e = a\bar{e}\gamma_5 e$"

$$j^{\mu}_{\mathrm{PQ}} = \frac{1}{2m_{\ell}}\left(\bar{g}_{\ell e}\bar{\ell}\gamma^{\mu}\ell + g_{\ell e}\bar{\ell}\gamma^{\mu}\gamma_5\ell + g_{\nu_{\ell}}\bar{\nu}_{\ell}\gamma^{\mu}P_L\nu_{\ell}\right)$$

$$j^{\mu}_{\mathrm{PQ}} = \frac{1}{2m_\ell}\left(\bar{g}_{\ell\ell}\bar{\ell}\gamma^\mu\ell + g_{\ell\ell}\bar{\ell}\gamma^\mu\gamma_5\ell + g_{\nu_\ell}\bar{\nu}_\ell\gamma^\mu P_L\nu_\ell\right)$$

Should we demand electroweak invariance ($\bar{g}_{\ell\ell} - g_{\ell\ell} = g_{\nu_\ell}$)?

$$j^{\mu}_{\mathrm{PQ}} = \frac{1}{2m_\ell}\left(\bar{g}_{\ell\ell}\bar{\ell}\gamma^{\mu}\ell + g_{\ell\ell}\bar{\ell}\gamma^{\mu}\gamma_5\ell + g_{\nu_\ell}\bar{\nu}_\ell\gamma^{\mu}P_L\nu_\ell\right)$$

Should we demand electroweak invariance ($\bar{g}_{\ell\ell} - g_{\ell\ell} = g_{\nu_\ell}$)?

Yes, duh...

- PQ charges are EW-symmetric
- Two parameters
- Benchmark model:
  $j^{\mu}_{\mathrm{PQ}} = \frac{g_{ee}}{m_e}\bar{e}\gamma_\mu P_R e$

$$j^\mu_{\mathrm{PQ}} = \frac{1}{2m_\ell}\left(\bar{g}_{\ell\ell}\bar{\ell}\gamma^\mu\ell + g_{\ell\ell}\bar{\ell}\gamma^\mu\gamma_5\ell + g_{\nu_\ell}\bar{\nu}_\ell\gamma^\mu P_L\nu_\ell\right)$$

Should we demand electroweak invariance ($\bar{g}_{\ell\ell} - g_{\ell\ell} = g_{\nu_\ell}$)?

Yes, duh...

- PQ charges are EW-symmetric
- Two parameters
- Benchmark model:
  $j^\mu_{\mathrm{PQ}} = \frac{g_{ee}}{m_e}\bar{e}\gamma_\mu P_R e$

No, duh...

- Generated through RG flow
- Also by $\partial^\mu a(HL)^\dagger\gamma_\mu(HL)$
- Benchmark model:
  $j^\mu_{\mathrm{PQ}} = \frac{g_{ee}}{2m_e}\bar{e}\gamma_\mu\gamma_5 e$

$$j^\mu_{\rm PQ} = \frac{1}{2m_\ell}\left(\bar{g}_{\ell\ell}\bar{\ell}\gamma^\mu\ell + g_{\ell\ell}\bar{\ell}\gamma^\mu\gamma_5\ell + g_{\nu_\ell}\bar{\nu}_\ell\gamma^\mu P_L\nu_\ell\right)$$

Majoron:	$\bar{g}_{\ell\ell} = g_{\nu_\ell}$,	$g_{\ell\ell} = 0$
DFSZ axion:	$\bar{g}_{\ell\ell} = g_{\ell\ell}$,	$g_{\nu_\ell} = 0$
KSVZ axion:	$g_{\ell\ell} \neq 0$,	$g_{\nu_\ell}, \bar{g}_{\ell\ell} \simeq 0$

Should we demand electroweak invariance ($\bar{g}_{\ell\ell} - g_{\ell\ell} = g_{\nu_\ell}$)?

Yes, duh...

- PQ charges are EW-symmetric
- Two parameters
- Benchmark model:
  $j^\mu_{\rm PQ} = \frac{g_{ee}}{m_e}\bar{e}\gamma_\mu P_R e$

No, duh...

- Generated through RG flow
- Also by $\partial^\mu a(HL)^\dagger\gamma_\mu(HL)$
- Benchmark model:
  $j^\mu_{\rm PQ} = \frac{g_{ee}}{2m_e}\bar{e}\gamma_\mu\gamma_5 e$

$$j^\mu_{\rm PQ} = \frac{1}{2m_\ell}\left(\bar{g}_{\ell\ell}\bar{\ell}\gamma^\mu\ell + g_{\ell\ell}\bar{\ell}\gamma^\mu\gamma_5\ell + g_{\nu_\ell}\bar{\nu}_\ell\gamma^\mu P_L\nu_\ell\right)$$

Majoron:	$\bar{g}_{\ell\ell} = g_{\nu_\ell}$,	$g_{\ell\ell} = 0$
DFSZ axion:	$\bar{g}_{\ell\ell} = g_{\ell\ell}$,	$g_{\nu_\ell} = 0$
KSVZ axion:	$g_{\ell\ell} \neq 0$,	$g_{\nu_\ell}, \bar{g}_{\ell\ell} \simeq 0$

Should we demand electroweak invariance ($\bar{g}_{\ell\ell} - g_{\ell\ell} = g_{\nu_\ell}$)?

Yes, duh...

- PQ charges are EW-symmetric
- Two parameters
- Benchmark model:
  $j^\mu_{\rm PQ} = \frac{g_{ee}}{m_e}\bar{e}\gamma_\mu P_R e$

No, duh...

- Generated through RG flow
- Also by $\partial^\mu a(HL)^\dagger\gamma_\mu(HL)$
- Benchmark model:
  $j^\mu_{\rm PQ} = \frac{g_{ee}}{2m_e}\bar{e}\gamma_\mu\gamma_5 e$

Whether or not this is required has dramatic consequences

$$\mathcal{L} = -a\partial_\mu j^\mu_{\mathrm{PQ}}$$

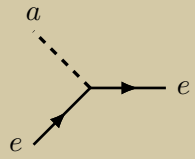
$$\mathcal{L} = -a\partial_\mu j^\mu_{\mathrm{PQ}}$$

$\partial_\mu j^\mu_{\mathrm{PQ}} =$

$$\mathcal{L} = -a\partial_\mu j^\mu_{\rm PQ}$$

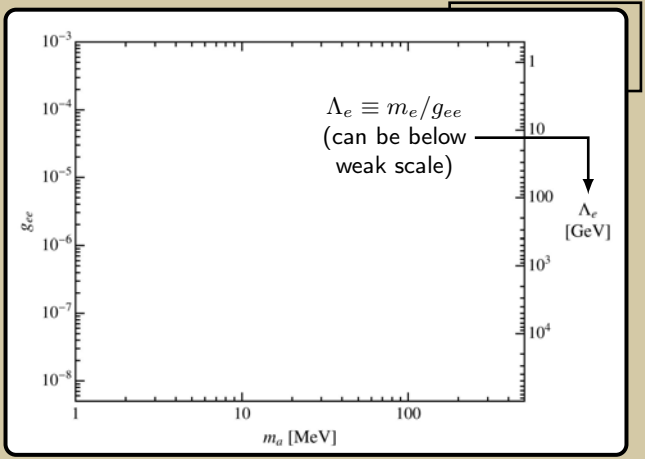
$$\partial_\mu j^\mu_{\rm PQ} = \quad g_{\ell\ell}(\bar{\ell} i\gamma_5 \ell)$$

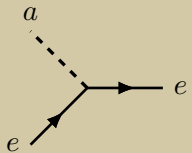
"Standard" form



$$\mathcal{L} = -a\partial_\mu j^\mu_{\rm PQ}$$

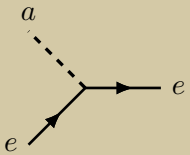
$$\partial_\mu j^\mu_{\rm PQ} = \; g_{\ell\ell}(\bar{\ell} i\gamma_5 \ell)$$

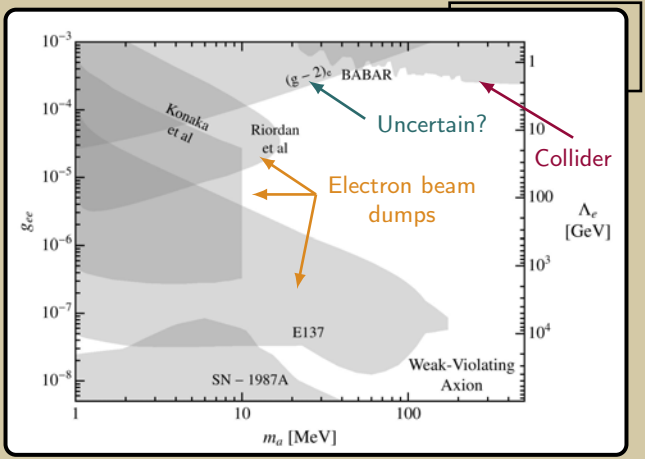




$$\mathcal{L} = -a\partial_\mu j^\mu_{\rm PQ}$$

$$\partial_\mu j^\mu_{\rm PQ} = \; g_{\ell\ell}(\bar{\ell} i\gamma_5 \ell)$$





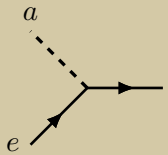
[**BABAR** - '14] , [**Riordan et al** - '87] , [**Bjorken et al** - '88], [**Bross et al** - '91]
[**Morel et al** - '20], [**Lucente, Carenza** - '21]

$$\mathcal{L} = -a\partial_\mu j^\mu_{\rm PQ}$$

$$\partial_\mu j^\mu_{\rm PQ} = \; g_{\ell\ell}(\bar{\ell} i\gamma_5 \ell)$$

$$-\frac{1}{64\pi^2}\frac{1}{m_\ell}(g_{\ell\ell} - \bar{g}_{\ell\ell} - g_{\nu_\ell}) g^2 W^+_{\mu\nu}\tilde{W}^{-\,\mu\nu} + \ldots$$

"Standard" form



Anomaly terms

$$\mathcal{L} = -a\partial_\mu j^\mu_{\rm PQ}$$

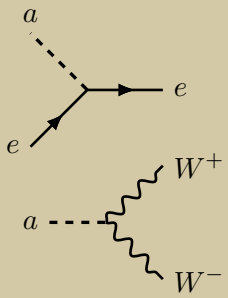
$$\partial_\mu j^\mu_{\rm PQ} = \; g_{\ell\ell}(\bar{\ell} i\gamma_5 \ell)$$

$$-\frac{1}{64\pi^2}\frac{1}{m_\ell}(g_{\ell\ell} - \bar{g}_{\ell\ell} - g_{\nu_\ell}) g^2 W^+_{\mu\nu}\tilde{W}^{-\,\mu\nu} + \ldots$$

$\propto 1/m_\ell$!

"Standard" form

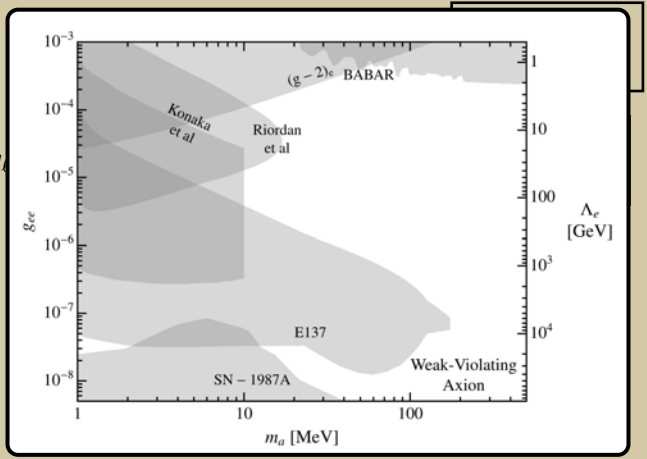
Anomaly terms

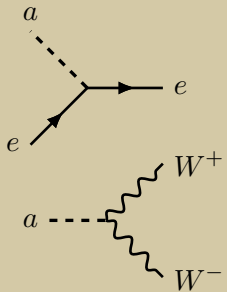


$$\mathcal{L} = -a\partial_\mu j^\mu_{\rm PQ}$$

$$\partial_\mu j^\mu_{\rm PQ} = \; g_{\ell\ell}(\bar{\ell} i\gamma_5 \ell)$$

$$-\frac{1}{64\pi^2}\frac{1}{m_\ell}(g$$

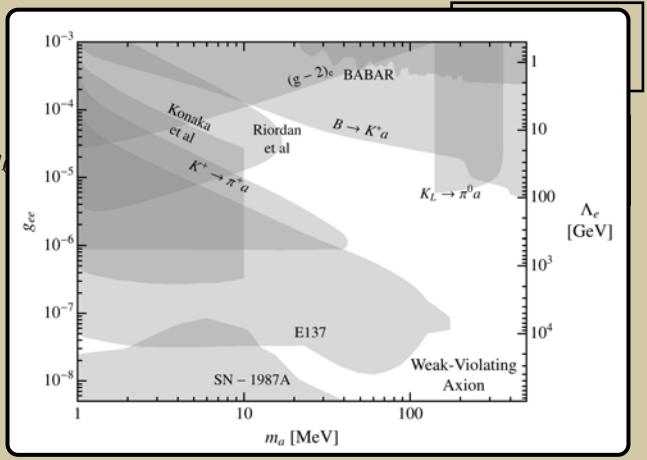


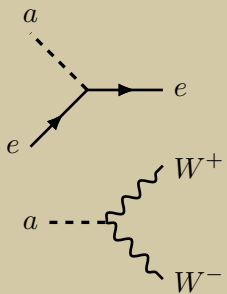


$$\mathcal{L} = -a\partial_\mu j^\mu_{\rm PQ}$$

$$\partial_\mu j^\mu_{\rm PQ} = \; g_{\ell\ell}(\bar{\ell} i\gamma_5 \ell)$$

$$-\frac{1}{64\pi^2}\frac{1}{m_\ell}(g$$



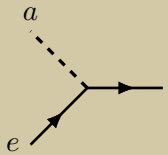


[**Bauer et al** - '21]

$$\mathcal{L} = -a\partial_\mu j^\mu_{\rm PQ}$$

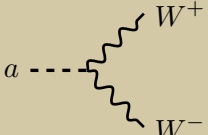
$$\partial_\mu j^\mu_{\rm PQ} = \; g_{\ell\ell}(\bar{\ell} i\gamma_5 \ell)$$

"Standard" form



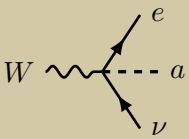
$$-\frac{1}{64\pi^2}\frac{1}{m_\ell}(g_{\ell\ell} - \bar{g}_{\ell\ell} - g_{\nu_\ell}) g^2 W^+_{\mu\nu}\tilde{W}^{-\,\mu\nu} + \ldots$$

Anomaly terms



$$+\frac{ig}{2\sqrt{2}}\frac{1}{m_\ell}(g_{\ell\ell} - \bar{g}_{\ell\ell} + g_{\nu_\ell})(\bar{\ell}\gamma^\mu P_L \nu_\ell) W^-_\mu \; + \; \text{h.c.}$$

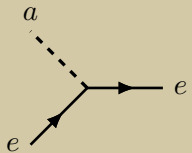
Weak vertex



$$\mathcal{L} = -a\partial_\mu j^\mu_{\rm PQ}$$

$$\partial_\mu j^\mu_{\rm PQ} = \; g_{\ell\ell}(\bar{\ell} i\gamma_5 \ell)$$

"Standard" form



$$-\frac{1}{64\pi^2}\frac{1}{m_\ell}(g_{\ell\ell} - \bar{g}_{\ell\ell} - g_{\nu_\ell}) g^2 W^+_{\mu\nu}\tilde{W}^{-\,\mu\nu} + \dots$$

Anomaly terms

$$+\frac{ig}{2\sqrt{2}}\frac{1}{m_\ell}(g_{\ell\ell} - \bar{g}_{\ell\ell} + g_{\nu_\ell})(\bar{\ell}\gamma^\mu P_L \nu_\ell) W^-_\mu \; + \; \text{h.c.}$$

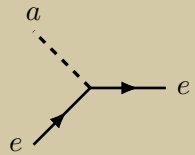
Weak vertex

$\propto 1/m_\ell$**!**

$$\mathcal{L} = -a\partial_\mu j^\mu_{\rm PQ}$$

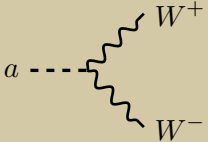
$$\partial_\mu j^\mu_{\rm PQ} = \; g_{\ell\ell}(\bar{\ell} i\gamma_5 \ell)$$

"Standard" form



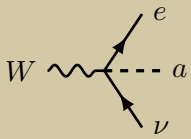
$$-\frac{1}{64\pi^2}\frac{1}{m_\ell}(g_{\ell\ell} - \bar{g}_{\ell\ell} - g_{\nu_\ell}) g^2 W^+_{\mu\nu}\tilde{W}^{-\,\mu\nu} + \ldots$$

Anomaly terms



$$+\frac{ig}{2\sqrt{2}}\frac{1}{m_\ell}(g_{\ell\ell} - \bar{g}_{\ell\ell} + g_{\nu_\ell})(\bar{\ell}\gamma^\mu P_L \nu_\ell) W^-_\mu \; + \; \text{h.c.}$$

Weak vertex



This work:

(1) Importance of weak vertex (2) New bound on standard vertex

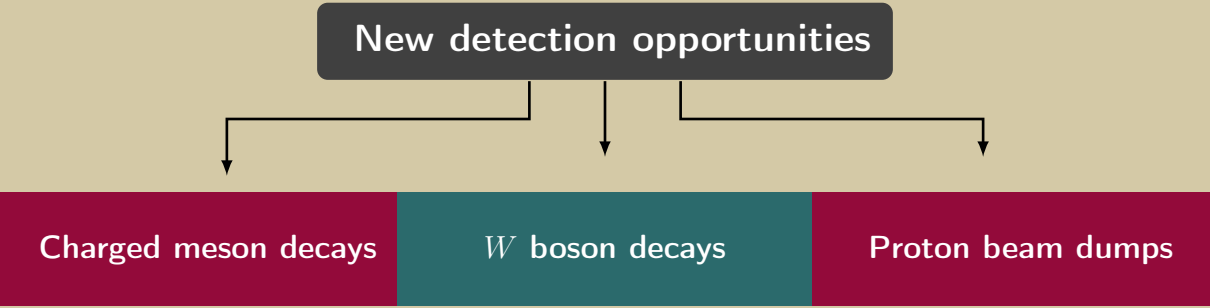
New detection opportunities

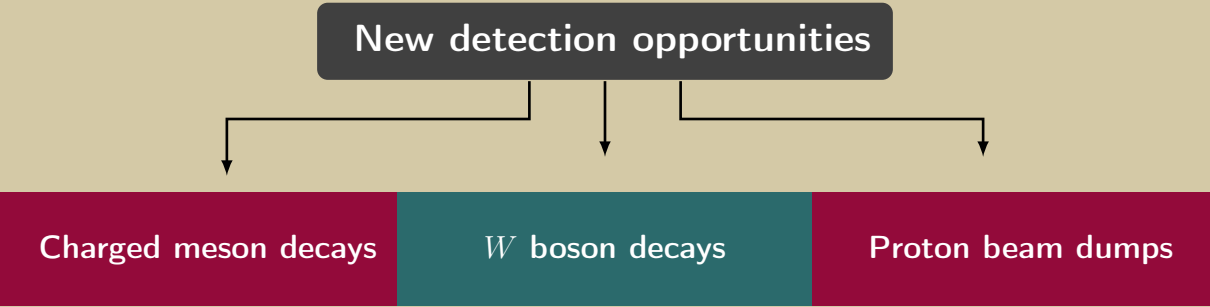
New detection opportunities

Charged meson decays

Relevant for all ALPs


New detection opportunities
Charged meson decays
W boson decays
Relevant for all ALPs
Relevant for weak-violating

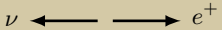

New detection opportunities
Charged meson decays
W boson decays
Proton beam dumps
Relevant for all ALPs
Relevant for weak-violating
Relevant for weak-violating



Focus on electron coupling

ALPs from π^+ decay*

↳ ALP removes helicity suppression

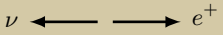


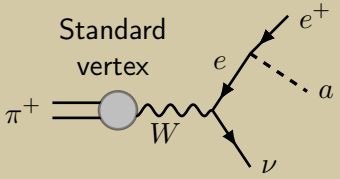
*ALP-π^0 mixing and quark coupling

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

ALPs from π^+ decay*

↳ ALP removes helicity suppression



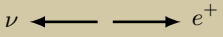


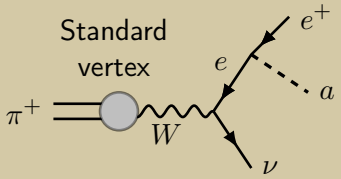
*ALP-π^0 mixing and quark coupling

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

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]

ALPs from π^+ decay*

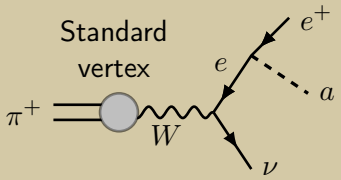
Weak-preserving

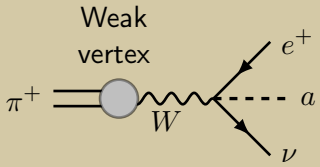
$$\Gamma_{\pi^+ \to e^+ \nu a} \propto g_{ee}^2 \frac{m_\pi^2 f_{\pi^+}^2}{m_W^4}$$

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

↳ ALP removes helicity suppression

$\nu \longleftarrow \longrightarrow e^+$



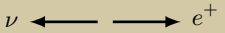


*ALP-π^0 mixing and quark coupling

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

ALPs from π^+ decay*

↳ ALP removes helicity suppression

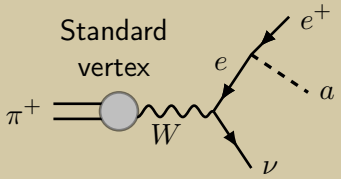


Weak-preserving

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

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

Standard vertex

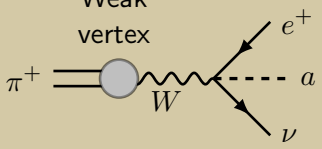


Weak-violating

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

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

Weak vertex

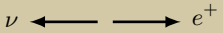


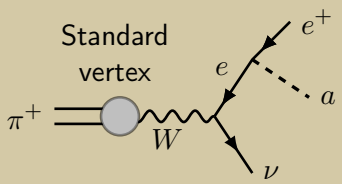
*ALP-π^0 mixing and quark coupling

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

ALPs from π^+ decay*

↳ ALP removes helicity suppression





Weak-preserving

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

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

Detectable

Weak-violating

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

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

*ALP-π^0 mixing and quark coupling

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

Experimental Capabilities

Experimental Capabilities

Past


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

SINDRUM Collaboration

Experimental Capabilities

Past

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

SINDRUM Collaboration

Experimental Capabilities

Past

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

SINDRUM Collaboration

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

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

Experimental Capabilities

Past

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

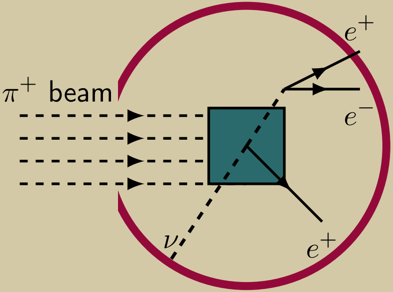
SINDRUM Collaboration

↳ 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



Experimental Capabilities

Past

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

SINDRUM Collaboration

Future

PSI Ring Cyclotron Proposal R-22-01.1

PIONEER: Studies of Rare Pion Decays

W. Altmannshofer | H. Binney | E. Blucher | D. Bryman | T. Cocolios

π^+

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

Experimental Capabilities

Past

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

SINDRUM Collaboration

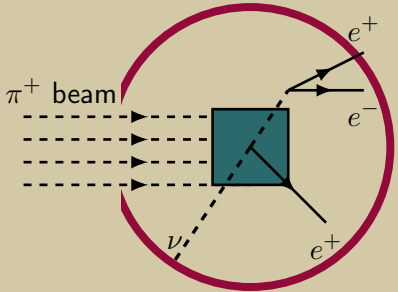
↳ Reached $\mathrm{Br}_{\pi^+\to e^+\nu a} \lesssim 10^{-10}$

Future

PSI Ring Cyclotron Proposal R-22-01.1

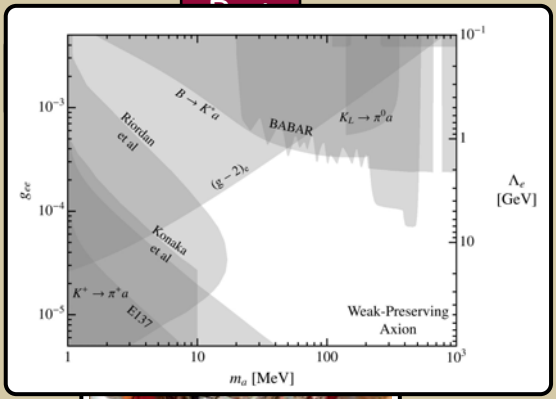
PIONEER: Studies of Rare Pion Decays

W. Altmannshofer | H. Binney | P. Blanchet | D. Bryman | L. Caminada



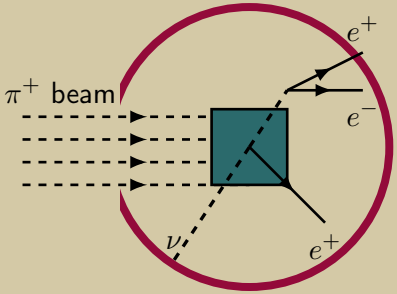
↳ Reach $\mathrm{Br}_{\pi^+\to e^+\nu a} \lesssim 10^{-11}$?

Experimental Capabilities



Future

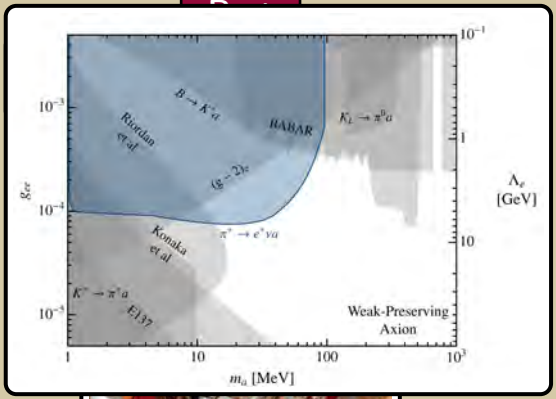
PSI Ring Cyclotron Proposal R-22-01.1
PIONEER: Studies of Rare Pion Decays



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

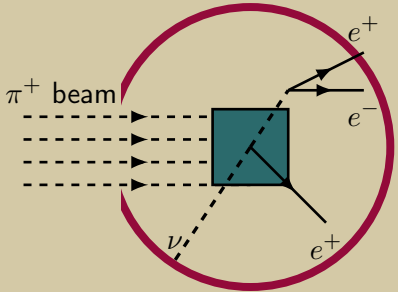
↳ Reach $\mathrm{Br}_{\pi^+ \to e^+ \nu a} \lesssim 10^{-11}$?

Experimental Capabilities



Future

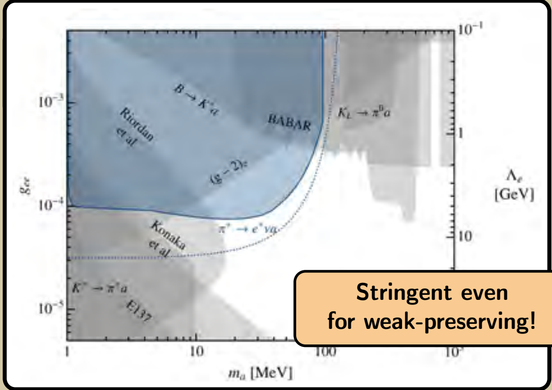
PSI Ring Cyclotron Proposal R-22-01.1
PIONEER: Studies of Rare Pion Decays



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

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

Experimental Capabilities

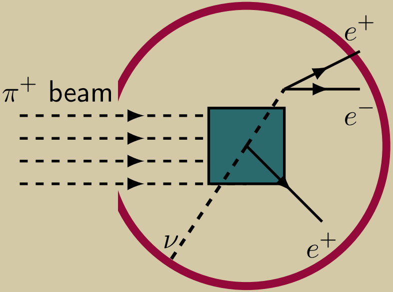


Stringent even for weak-preserving!

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

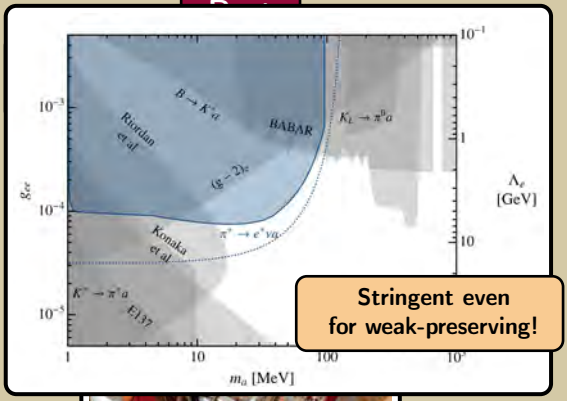
Future

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

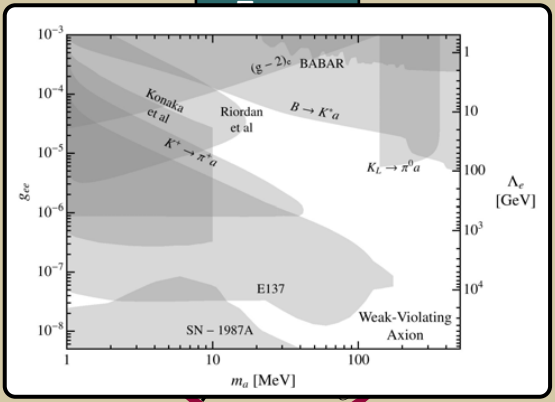


↳ Reach $\mathrm{Br}_{\pi^+ \to e^+ \nu a} \lesssim 10^{-11}$?

Experimental Capabilities



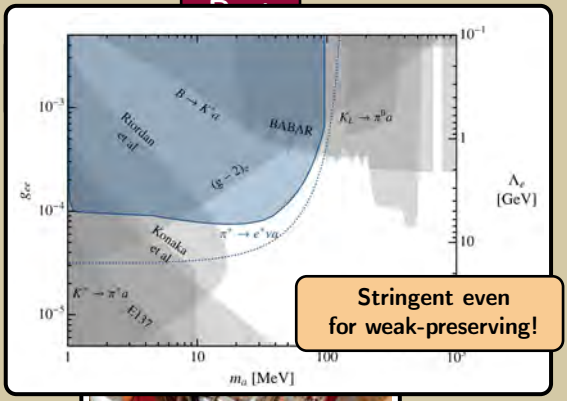
Stringent even for weak-preserving!



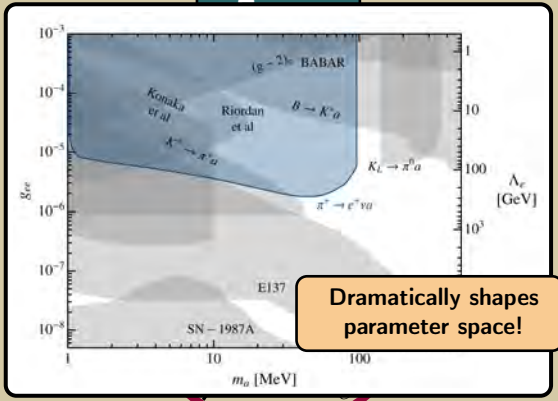
↳ Reached $\mathrm{Br}_{\pi^+ \to e^+ \nu a} \lesssim 10^{-10}$

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

Experimental Capabilities



Stringent even for weak-preserving!

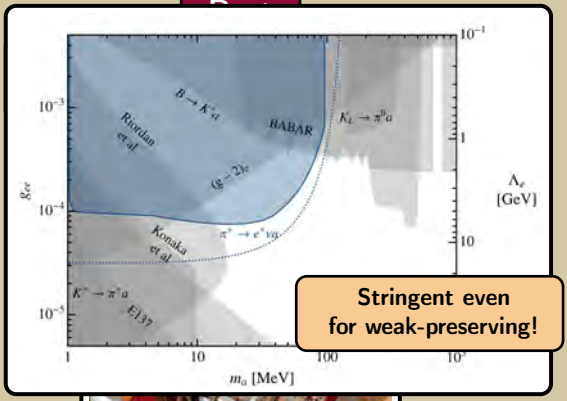


Dramatically shapes parameter space!

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

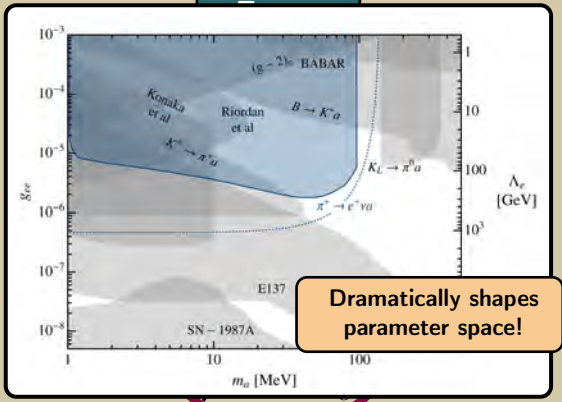
↳ Reach $\mathrm{Br}_{\pi^+ \to e^+ \nu a} \lesssim 10^{-11}$?

Experimental Capabilities



Stringent even for weak-preserving!

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



Dramatically shapes parameter space!

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

Other charged mesons

Win by m^2_{meson}/m^2_e

Kaons

- $K^+ \to e^+\nu$ is small ($\Gamma \propto m_e^2$)
- Search for $K^+ \to e^+\nu e^+ e^-$

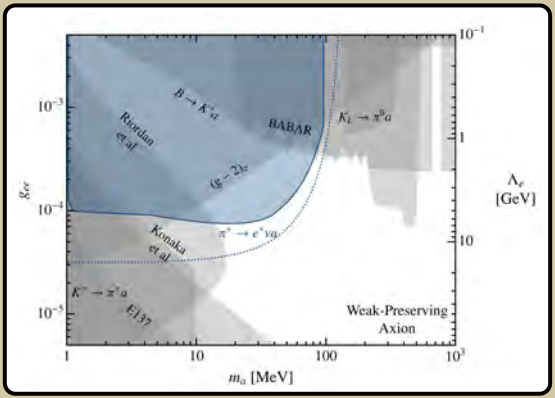
$$\text{Br}_{K^+ \to e^+\nu a} \lesssim 3 \times 10^{-8}$$

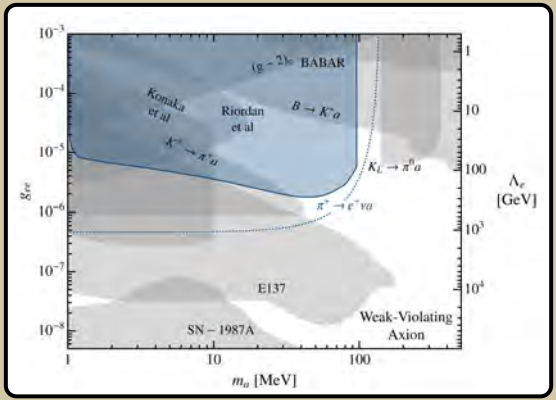
[Exp 865 - '02]

- Improve with Kaon factories

Other charged mesons

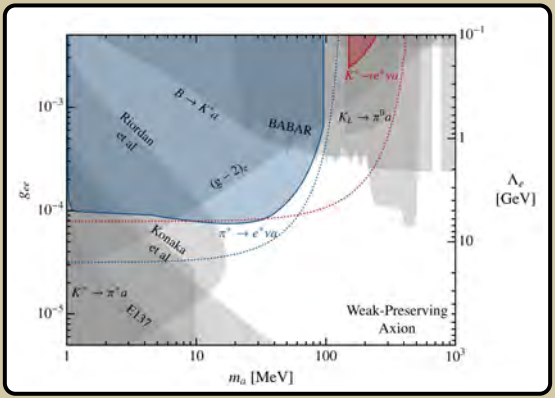
Win by m^2_{meson}/m^2_e

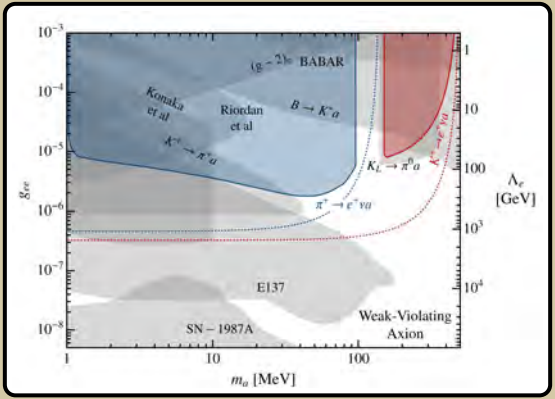




Other charged mesons

Win by m^2_{meson}/m^2_e





Other charged mesons

Win by m^2_{meson}/m^2_e

Kaons

- $K^+ \to e^+\nu$ is small ($\Gamma \propto m_e^2$)
- Search for $K^+ \to e^+\nu e^+ e^-$

$$\text{Br}_{K^+\to e^+\nu a} \lesssim 3 \times 10^{-8}$$

[Exp 865 - '02]

- Improve with Kaon factories

$D/D_s/B/B_c$ mesons

- Large flavor preserving decays
- Suppresses branching ratio
- D_s/B_c win by CKM factor
- Need to reach $\mathcal{O}(10^{-6})$

W^+ boson decay

W^+ boson decay

W boson decay width $\propto m_W^2/m_e^2$ for weak-violating ALP

$$\mathrm{Br}_{W^+\to e^+\nu a} \sim \left(\frac{\bar{g}_{ee}}{10^{-3}}\right)^2$$

Irrelevant for weak-preserving

W^+ boson decay

W boson decay width $\propto m_W^2/m_e^2$ for weak-violating ALP

$$\mathrm{Br}_{W^+\to e^+\nu a} \sim \left(\frac{\bar{g}_{ee}}{10^{-3}}\right)^2$$

Irrelevant for weak-preserving

Bound on rare W-boson decays?

W+ DECAY MODES		Fraction (Γ_i/Γ)	Confidence level	p (MeV/c)
$\ell^+\nu$	[b]	(10.86 ± 0.09) %		–
$e^+\nu$		(10.71 ± 0.16) %		40189
$\mu^+\nu$		(10.63 ± 0.15) %		40189
$\tau^+\nu$		(11.38 ± 0.21) %		40170
hadrons		(67.41 ± 0.27) %		–
$\pi^+\gamma$		$< 7 \times 10^{-6}$	95%	40189
$D_s^+\gamma$		$< 1.3 \times 10^{-3}$	95%	40165
cX		(33.3 ± 2.6) %		–
$c\bar{s}$		$(31\ ^{+13}_{-11})$ %		–
invisible	[c]	(1.4 ± 2.9) %		–
$\pi^+\pi^+\pi^-$		$< 1.01 \times 10^{-6}$	95%	40189

W^+ boson decay

W boson decay width $\propto m_W^2/m_e^2$ for weak-violating ALP → $\mathrm{Br}_{W^+\to e^+\nu a} \sim \left(\frac{\bar{g}_{ee}}{10^{-3}}\right)^2$ **Irrelevant for weak-preserving**

Bound on rare W-boson decays?

W+ DECAY MODES		Fraction (Γ_i/Γ)	Confidence level	p (MeV/c)
$\ell^+\nu$	[b]	(10.86 ± 0.09) %		–
$e^+\nu$		(10.71 ± 0.16) %		40189
$\mu^+\nu$		(10.63 ± 0.15) %		40189
$\tau^+\nu$		(11.38 ± 0.21) %		40170
hadrons		(67.41 ± 0.27) %		–
$\pi^+\gamma$		< 7 × 10^{-6}	95%	40189
$D_s^+\gamma$		< 1.3 × 10^{-3}	95%	40165
cX		(33.3 ± 2.6) %		–
$c\bar{s}$		(31 $^{+13}_{-11}$) %		–
invisible	[c]	(1.4 ± 2.9) %		–
$\pi^+\pi^+\pi^-$		< 1.01 × 10^{-6}	95%	40189

↳ Contribute to total width,

$$\Gamma_W = 2.085 \pm 0.04 \text{ GeV}$$

$$\mathrm{Br}_{W^+\to e^+\nu a} \lesssim 0.04$$

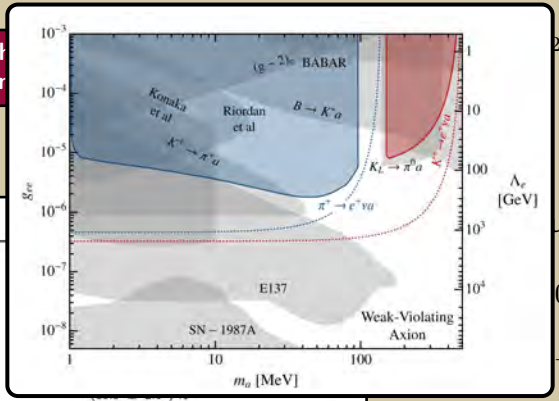
↳ Dedicated search:

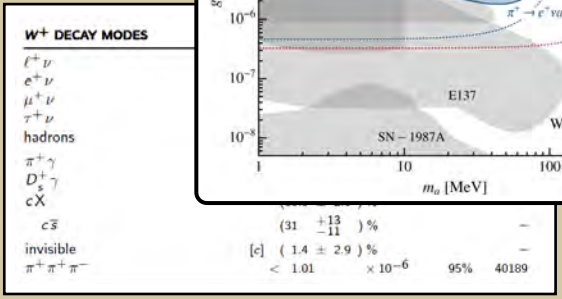
$$\mathrm{Br}_{W^+\to e^+\nu a} \lesssim \mathcal{O}(10^{-5})$$

W^+ boson decay

W boson decay width for weak-violatin

Irrelevant for weak-preserving





W+ DECAY MODES

$\ell^+\nu$				
$e^+\nu$				
$\mu^+\nu$				
$\tau^+\nu$				
hadrons				
$\pi^+\gamma$				
$D_s^+\gamma$				
cX				
$c\overline{s}$	$(31\ ^{+13}_{-11})\ \%$			–
invisible	[c] $(1.4 \pm 2.9)\ \%$			–
$\pi^+\pi^+\pi^-$	< 1.01	$\times 10^{-6}$	95%	40189

ute to total width,

085 ± 0.04 GeV

$\to e^+\nu a \lesssim 0.04$

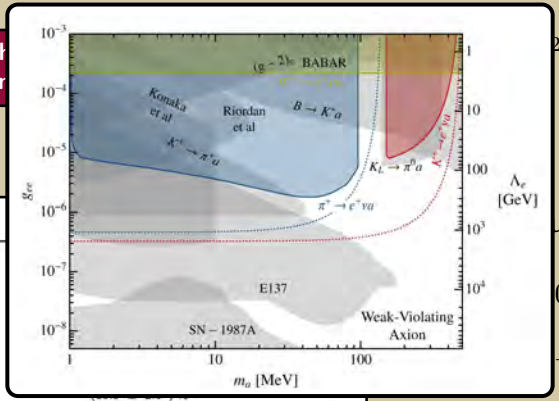
↳ Dedicated search:

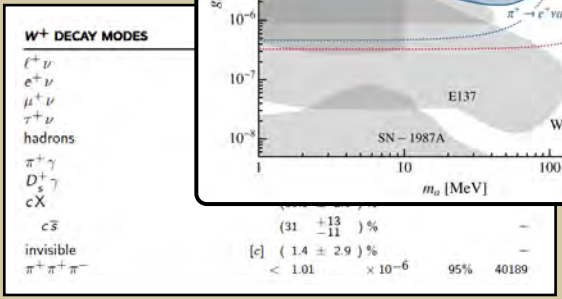
$\mathrm{Br}_{W^+ \to e^+\nu a} \lesssim \mathcal{O}(10^{-5})$

W^+ boson decay

W boson decay width for weak-violatin

Irrelevant for weak-preserving





W+ DECAY MODES

$\ell^+\nu$				
$e^+\nu$				
$\mu^+\nu$				
$\tau^+\nu$				
hadrons				
$\pi^+\gamma$				
$D_s^+\gamma$				
cX				
$c\overline{s}$	$(31\ ^{+13}_{-11})\ \%$			–
invisible	[c] $(1.4 \pm 2.9)\ \%$			–
$\pi^+\pi^+\pi^-$	< 1.01	$\times 10^{-6}$	95%	40189

ute to total width,

085 ± 0.04 GeV

$\to e^+\nu a \lesssim 0.04$

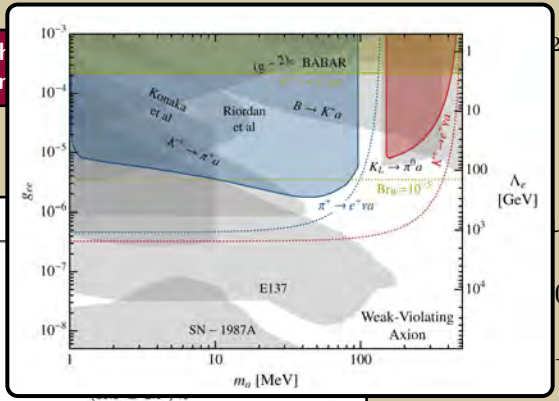
↳ Dedicated search:

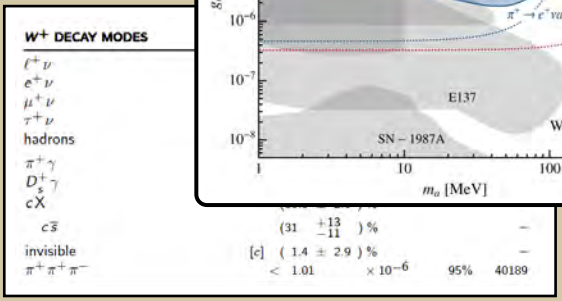
$\mathrm{Br}_{W^+ \to e^+\nu a} \lesssim \mathcal{O}(10^{-5})$

W^+ boson decay

W boson decay width for weak-violatin

Irrelevant for weak-preserving





W+ DECAY MODES

$\ell^+\nu$				
$e^+\nu$				
$\mu^+\nu$				
$\tau^+\nu$				
hadrons				
$\pi^+\gamma$				
$D_s^+\gamma$				
cX				
$c\overline{s}$	(31 $^{+13}_{-11}$) %			–
invisible	[c] (1.4 ± 2.9) %			–
$\pi^+\pi^+\pi^-$	< 1.01	$\times 10^{-6}$	95%	40189

ute to total width,

085 ± 0.04 GeV

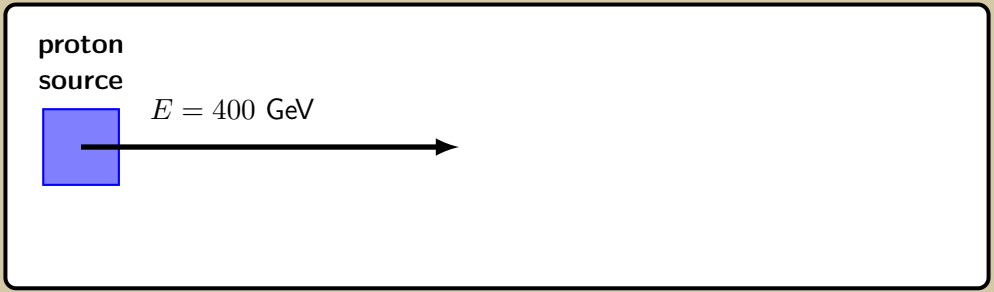
$\to e^+\nu a \lesssim 0.04$

↳ Dedicated search:

$\mathrm{Br}_{W^+ \to e^+\nu a} \lesssim \mathcal{O}(10^{-5})$

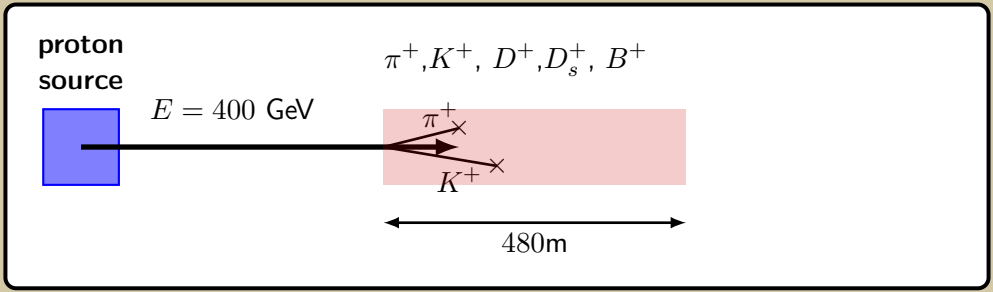
Proton beam dump experiments

Ex: CHARM experiment



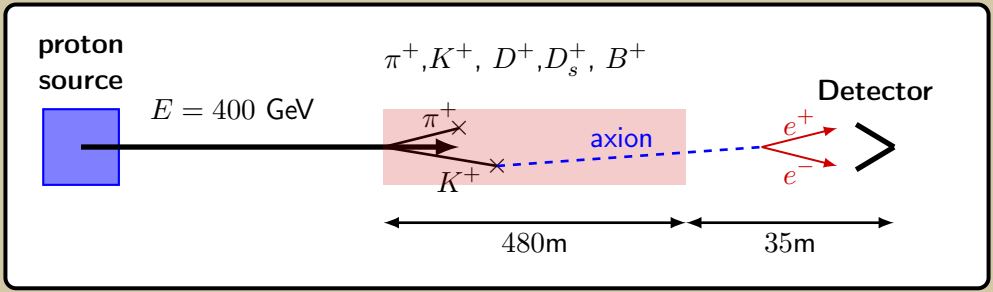
Proton beam dump experiments

Ex: CHARM experiment



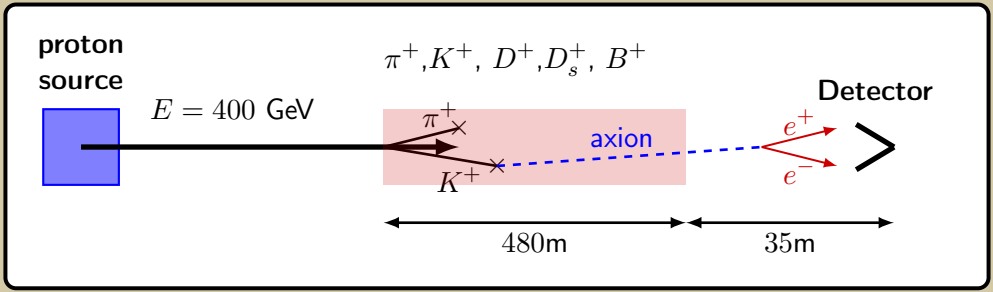
Proton beam dump experiments

Ex: CHARM experiment



Proton beam dump experiments

Ex: CHARM experiment



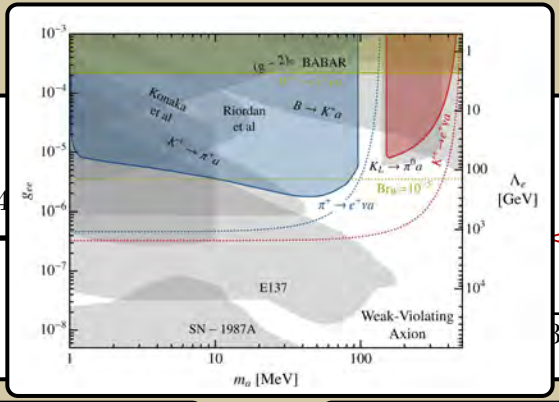
First use of D, D_s, B_c mesons

Observed zero events [CHARM - 1985]

Proton beam dump experiments

proton source

$E = 4$



Detector

e^+

e^-

35m

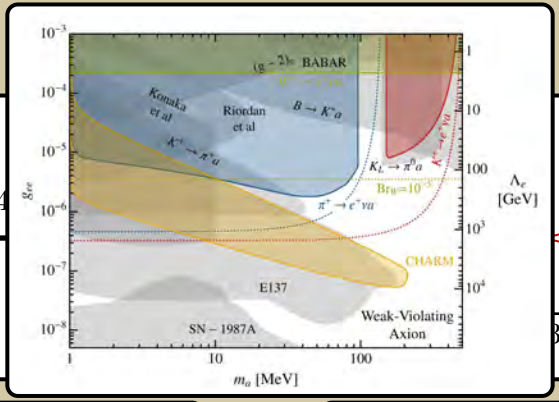
First use of D, D_s, B_c mesons

Observed zero events [CHARM - 1985]

Proton beam dump experiments

proton source

$E = 4$



Detector

e^+

e^-

35m

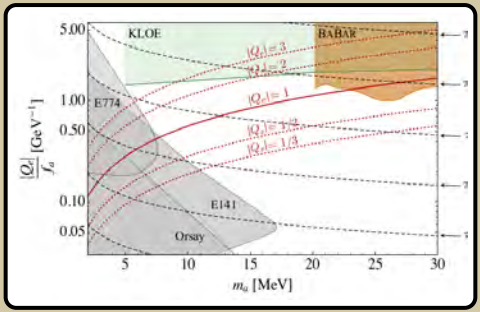
First use of D, D_s, B_c mesons

Observed zero events [CHARM - 1985]

Implications

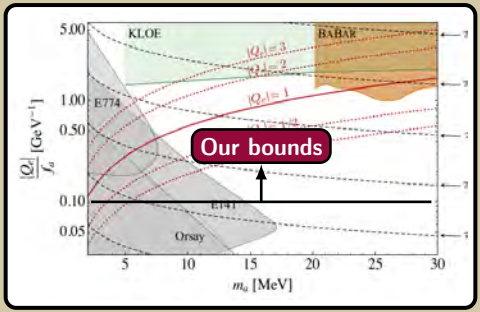
Implications

[Alves, Weiner - '17] , [Alves - '21] revisited possibility of MeV QCD axion



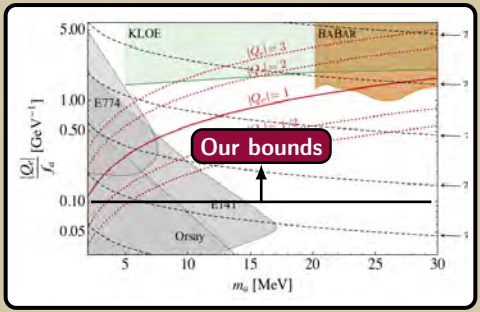
Implications

[Alves, Weiner - '17] , [Alves - '21] revisited possibility of MeV QCD axion

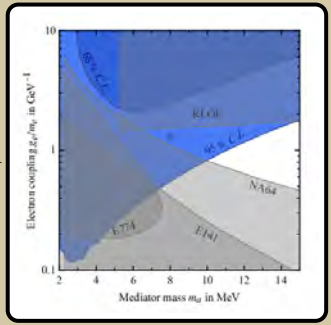


Implications

[Alves, Weiner - '17] , [Alves - '21] revisited possibility of MeV QCD axion

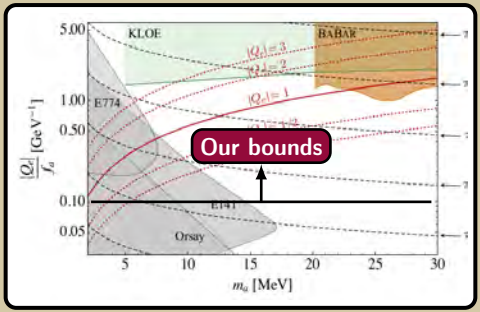


[Buttazzo et al - '21] propose ALP mediate Xenon-1T excess

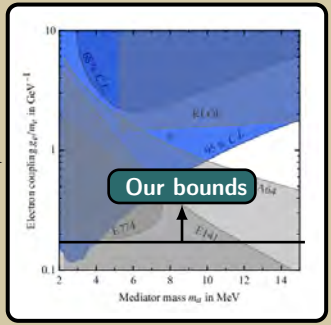


Implications

[Alves, Weiner - '17] , [Alves - '21] revisited possibility of MeV QCD axion

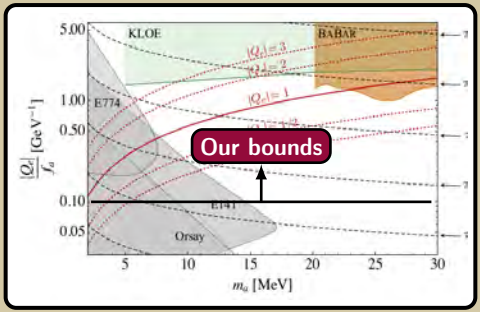


[Buttazzo et al - '21] propose ALP mediate Xenon-1T excess

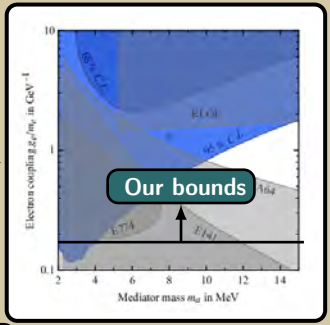


Implications

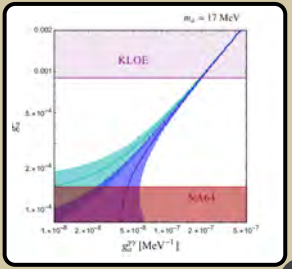
[Alves, Weiner - '17] , [Alves - '21] revisited possibility of MeV QCD axion



[Buttazzo et al - '21] propose ALP mediate Xenon-1T excess

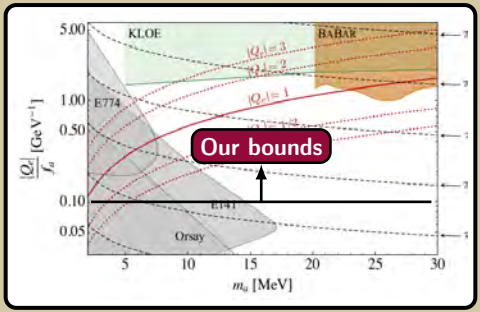


[Liu, McGinnis, Wagner, Wan - '21], ALP for Atomki excess

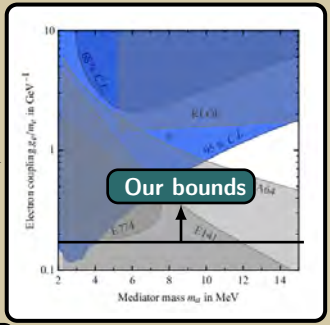


Implications

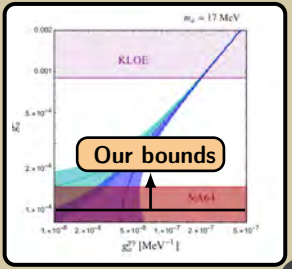
[Alves, Weiner - '17] , [Alves - '21] revisited possibility of MeV QCD axion



[Buttazzo et al - '21] propose ALP mediate Xenon-1T excess



[Liu, McGinnis, Wagner, Wan - '21], ALP for Atomki excess



Summary

Revisited theory of leptophilic ALPs

weak-preserving | Need to distinguish | **weak-violating**

Strong bounds in either case

Charged meson decays | W boson decays | Proton beam dumps

Summary

Revisited theory of leptophilic ALPs

weak-preserving | Need to distinguish | **weak-violating**

Strong bounds in either case

Charged meson decays | W boson decays | Proton beam dumps

Final musings

Weak-violating ALPs drive new phenomenology

Every model has some weak-violation. Implications?