

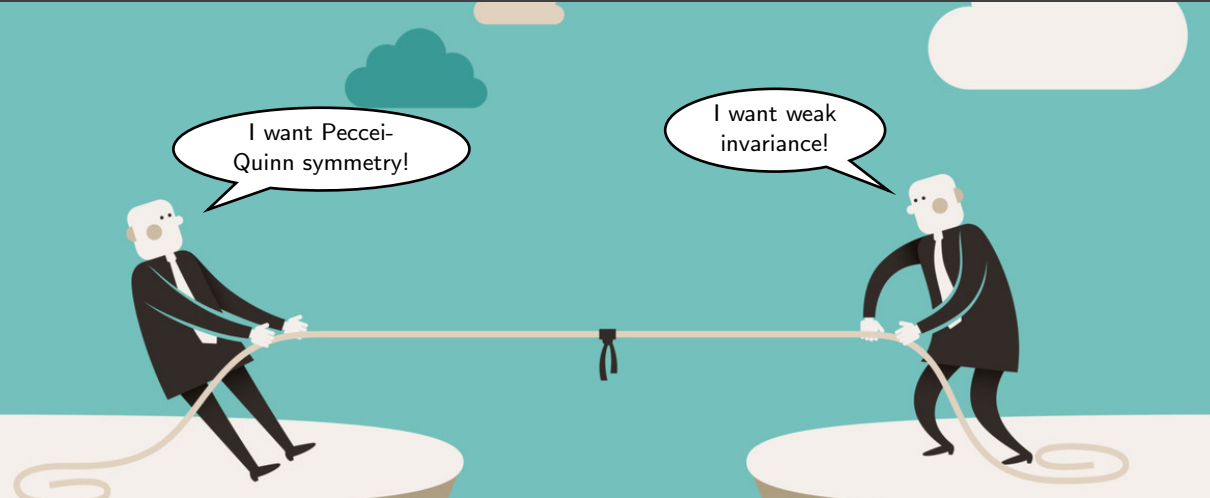
New Insights Into Axion-Lepton Interactions

New Physics @
Korea Institute

Jeff Dror

[2209.00665]
[?]

w/ Altmannshofer, Gori
... w/ Guerrero, Rigolin



I want Peccei-
Quinn symmetry!

I want weak
invariance!

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

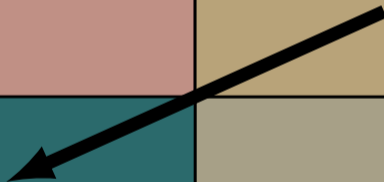
Outline

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

Lepton-Axion Effective Theory

$$\mathcal{L} = \partial_\mu a j_{PQ}^\mu$$

Lepton-Axion Effective Theory

$$\mathcal{L} = \partial_\mu a j_{\text{PQ}}^\mu$$

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

Lepton-Axion Effective Theory

$$\mathcal{L} = \partial_\mu a j_{\text{PQ}}^\mu$$

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

Is the vector
coupling
physical?

Is $\partial_\mu a \bar{\ell} \gamma^\mu \gamma_5 \ell$
 $= -m_\ell a \bar{\ell} \gamma_5 \ell$?

Is the neutrino
term $\propto m_\nu$?

Lepton-Axion Effective Theory

$$\mathcal{L} = \partial_\mu a j_{\text{PQ}}^\mu$$

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

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

Lepton-Axion Effective Theory

$$\mathcal{L} = \partial_\mu a j_{\text{PQ}}^\mu$$

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

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

Ne.

네.

Yes.

A-ni-yo.

아니요.

No.

Lepton-Axion Effective Theory

$$\mathcal{L} = \partial_\mu a j_{\text{PQ}}^\mu$$

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

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

Ne

PQ charges of SM fermions
are EW-symmetric

Lepton-Axion Effective Theory

$$\mathcal{L} = \partial_\mu a j_{\text{PQ}}^\mu$$

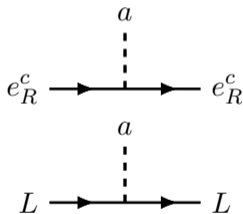
$$j_{\text{PQ}}^\mu = \frac{1}{2m_\ell} \left(\bar{g}_{\ell\ell} \bar{\ell} \gamma^\mu \ell + g_{\ell\ell} \bar{\ell} \gamma^\mu \gamma_5 \ell + g_{\nu_\ell} \bar{\nu}_\ell \gamma^\mu P_L \nu_\ell \right)$$

Should we demand electroweak invariance

($\bar{a}_{\text{EW}} = a_{\text{EW}} = a$)?

Ne

PQ charges of SM fermions
are EW-symmetric



Lepton-Axion Effective Theory

$$\mathcal{L} = \partial_\mu a j_{\text{PQ}}^\mu$$

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

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

Ne

PQ charges of SM fermions
are EW-symmetric

3 \rightarrow 2
parameters

benchmark:

$$j_{\text{PQ}}^\mu = \frac{g_{ee}}{m_e} \bar{e} \gamma_\mu P_R e$$

DFSZ-like

Lepton-Axion Effective Theory

$$\mathcal{L} = \partial_\mu a j_{\text{PQ}}^\mu$$

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

Should we demand electroweak invariance

$$(\bar{g}_{\ell\ell} - g_{\ell\ell} = g_{\nu_\ell})?$$

Ne

A-ni-yo

PQ charges of SM fermions
are EW-symmetric

3 \rightarrow 2
parameters

benchmark:

$$j_{\text{PQ}}^\mu = \frac{g_{ee}}{m_e} \bar{e} \gamma_\mu P_R e$$

DFSZ-like

SM fermion may not
be directly charged

Lepton-Axion Effective Theory

$$\mathcal{L} = \partial_\mu a j_{\text{PQ}}^\mu$$

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

Should we demand electroweak invariance

$$(\bar{a}_{\text{EW}} - a_{\text{EW}} = a_{\text{EW}})?$$

Ne

A-ni-yo

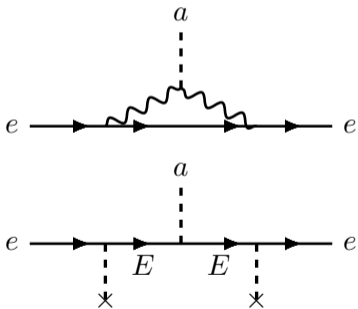
PQ charges of SM fermions are EW-symmetric

3 \rightarrow 2 parameters

benchmark

$$j_{\text{PQ}}^\mu = \frac{g_{\ell\ell}}{m_\ell}$$

DFSZ-like



fermion may not be directly charged

Lepton-Axion Effective Theory

$$\mathcal{L} = \partial_\mu a j_{\text{PQ}}^\mu$$

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

Should we demand electroweak invariance

$$(\bar{g}_{\ell\ell} - g_{\ell\ell} = g_{\nu_\ell})?$$

Ne

A-ni-yo

PQ charges of SM fermions
are EW-symmetric

3 \rightarrow 2
parameters

benchmark:

$$j_{\text{PQ}}^\mu = \frac{g_{ee}}{m_e} \bar{e} \gamma_\mu P_R e$$

DFSZ-like

SM fermion may not
be directly charged

RG flow

$$\partial^\mu a (HL)^\dagger \gamma_\mu (HL)$$

benchmark:
$$j_{\text{PQ}}^\mu = \frac{g_{ee}}{2m_e} \bar{e} \gamma_\mu \gamma_5 e$$

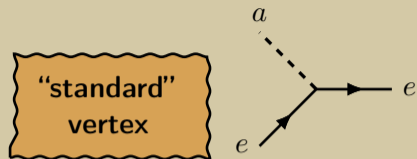
KSVZ-like

$$\mathcal{L} = -a\partial_\mu j_{PQ}^\mu$$

$$\partial_\mu j_{PQ}^\mu =$$

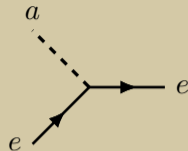
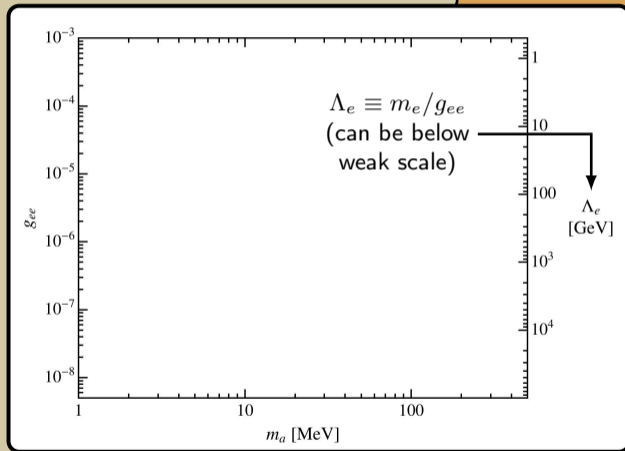
$$\mathcal{L} = -a\partial_\mu j_{PQ}^\mu$$

$$\partial_\mu j_{PQ}^\mu = g_{\ell\ell}(\bar{\ell}i\gamma_5\ell) + \dots$$



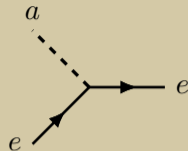
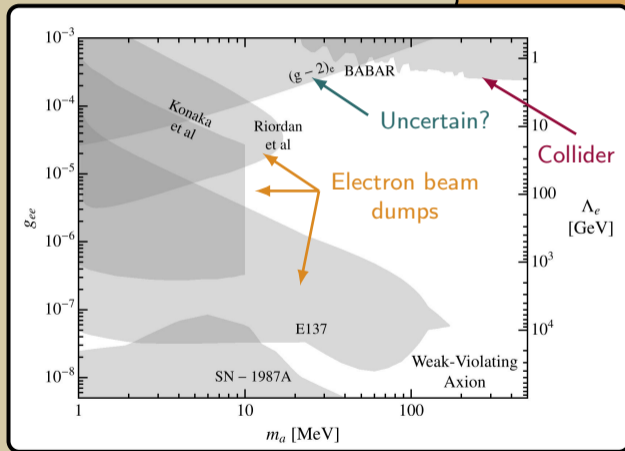
$$\mathcal{L} = -a \partial_\mu j_{PQ}^\mu$$

$$\partial_\mu j_{PQ}^\mu = g_{ee} (\bar{\ell} i \gamma_5 \ell)$$



$$\mathcal{L} = -a\partial_\mu j_{PQ}^\mu$$

$$\partial_\mu j_{PQ}^\mu = g_{ee}(\bar{\ell}i\gamma_5\ell)$$



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

$$\mathcal{L} = -a \partial_\mu j_{PQ}^\mu$$

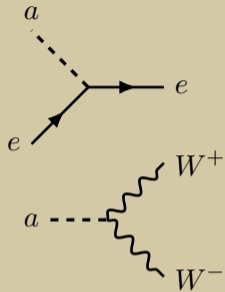
$$\partial_\mu j_{PQ}^\mu = g_{\ell\ell} (\bar{\ell} i \gamma_5 \ell)$$

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

+ ...

“standard”
vertex

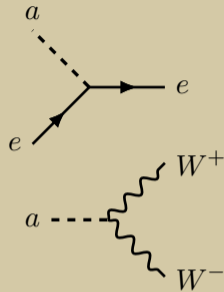
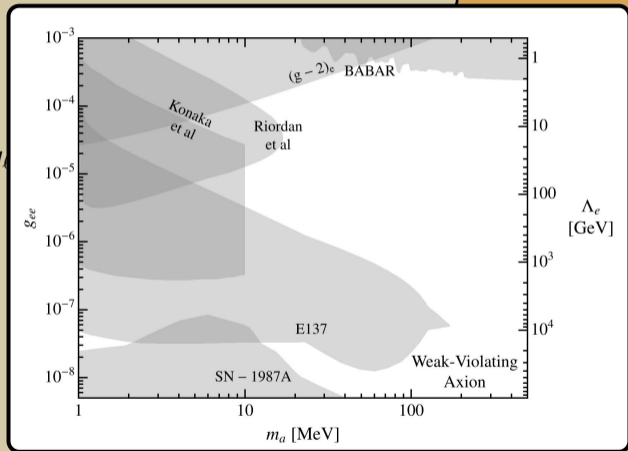
anomaly
terms



$$\mathcal{L} = -a\partial_\mu j_{PQ}^\mu$$

$$\partial_\mu j_{PQ}^\mu = g_{ee}(\bar{\ell}i\gamma_5\ell)$$

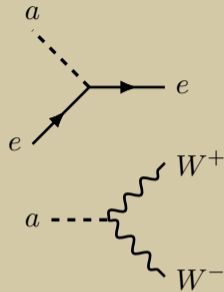
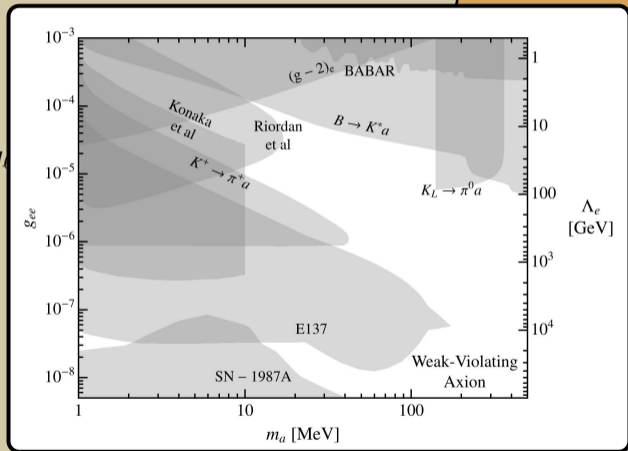
$$-\frac{1}{64\pi^2} \frac{1}{m_\ell} (g_{ee})$$



$$\mathcal{L} = -a \partial_\mu j_{PQ}^\mu$$

$$\partial_\mu j_{PQ}^\mu = g_{\ell\ell} (\bar{\ell} i \gamma_5 \ell)$$

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



[Bauer, Neubert, et al - '17, '21]

$$\mathcal{L} = -a\partial_\mu j_{PQ}^\mu$$

$$\partial_\mu j_{PQ}^\mu = g_{\ell\ell}(\bar{\ell}i\gamma_5\ell)$$

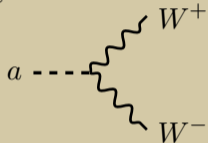
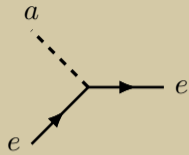
$$-\frac{1}{64\pi^2}\frac{1}{m_\ell}(g_{\ell\ell} - \bar{g}_{\ell\ell} - g_{\nu\ell})g^2W_{\mu\nu}^+\tilde{W}^{-\mu\nu} + \dots$$

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

“standard”
vertex

anomaly
terms

weak
vertex



$$\mathcal{L} = -a\partial_\mu j_{PQ}^\mu$$

$$\partial_\mu j_{PQ}^\mu = g_{\ell\ell}(\bar{\ell}i\gamma_5\ell)$$

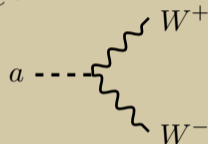
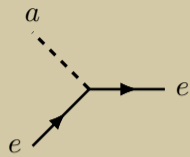
$$-\frac{1}{64\pi^2}\frac{1}{m_\ell}(g_{\ell\ell} - \bar{g}_{\ell\ell} - g_{\nu\ell})g^2W_{\mu\nu}^+\tilde{W}^{-\mu\nu} + \dots$$

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

“standard”
vertex

anomaly
terms

weak
vertex



This work:

- 1 Importance of weak vertex
- 2 New bound on standard vertex

$$\mathcal{L} = -a\partial_\mu j_{PQ}^\mu$$

$$\partial_\mu j_{PQ}^\mu = g_{\ell\ell}(\bar{\ell}i\gamma_5\ell)$$

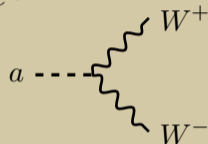
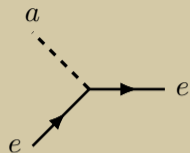
$$-\frac{1}{64\pi^2}\frac{1}{m_\ell}(g_{\ell\ell} - \bar{g}_{\ell\ell} - g_{\nu\ell})g^2W_{\mu\nu}^+\tilde{W}^{-\mu\nu} + \dots$$

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

“standard”
vertex

anomaly
terms

weak
vertex



This work:

- 1 Importance of weak vertex
- 2 New bound on standard vertex

charged
meson
decays

W^\pm boson
decays

proton
beam
dumps

ALPs from π^+ decay*

↳ ALP removes helicity suppression

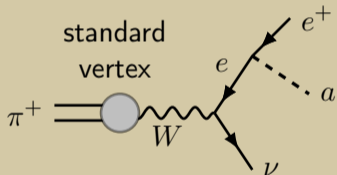
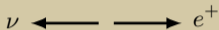
$$\nu \longleftrightarrow e^+$$

*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

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

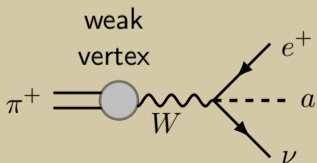
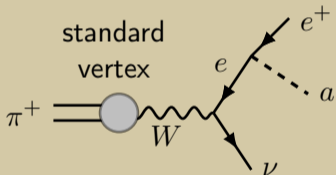
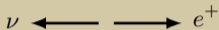
$$\text{Br}(\pi^+ \rightarrow e^+ \nu a) \simeq 1.0 \times 10^{-8} \left(\frac{g_{ee}}{10^{-3}} \right)^2$$

*ALP- π^0 mixing and quark coupling

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

ALPs from π^+ decay*

↳ ALP removes helicity suppression



Weak-preserving

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

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

Weak-violating

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

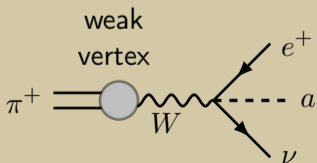
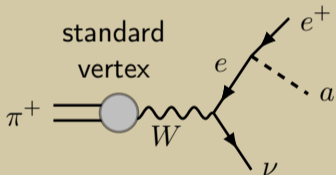
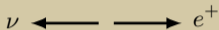
$$\text{Br}(\pi^+ \rightarrow e^+ \nu a) \simeq 4.5 \times 10^{-5} \left(\frac{g_{ee}}{10^{-3}} \right)^2$$

*ALP- π^0 mixing and quark coupling

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

ALPs from π^+ decay*

↳ ALP removes helicity suppression



Weak-preserving

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

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

Detectable

Weak-violating

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

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

*ALP- π^0 mixing and quark coupling

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

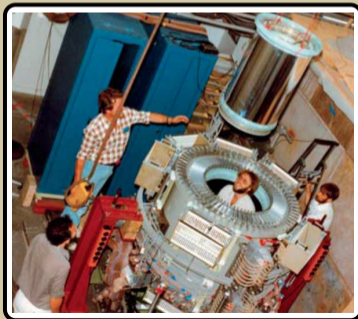
Experimental Capabilities

Experimental Capabilities



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

SINDRUM Collaboration



Experimental Capabilities



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

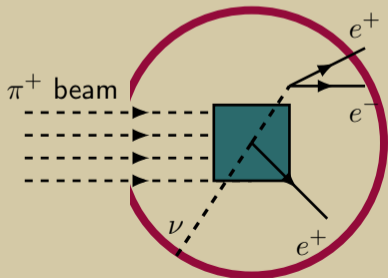
SINDRUM Collaboration



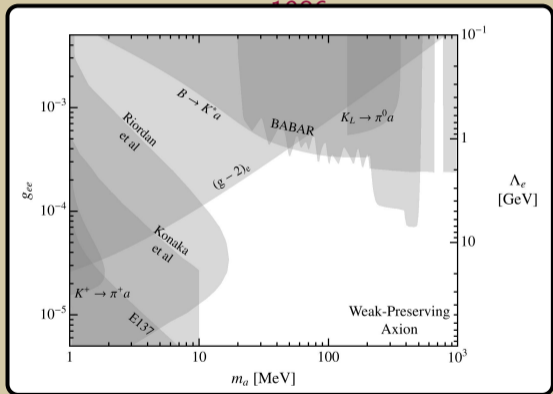
PSI Ring Cyclotron Proposal R-22-01.1

PIONEER: Studies of Rare Pion Decays

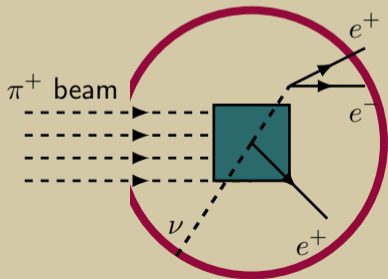
*W. Altmannshofer*¹, *H. Rinnar*², *E. Blucher*³, *D. Reunan*^{4,5}, *I. Caminada*⁶



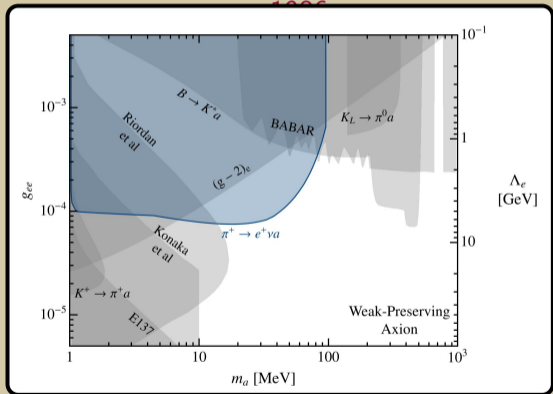
Experimental Capabilities



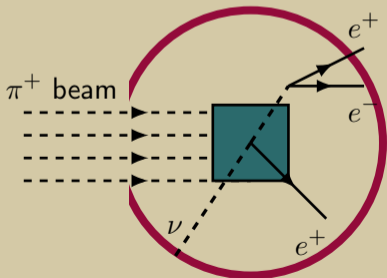
PSI Ring Cyclotron Proposal R-22-01.1
 PIONEER: Studies of Rare Pion Decays
 W. Altmannshofer¹, H. Rinnar², E. Blucher³, D. Reunanen^{4,5}, I. Caminata⁶



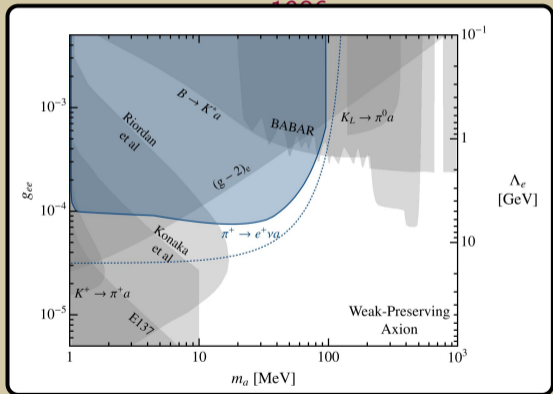
Experimental Capabilities



PSI Ring Cyclotron Proposal R-22-01.1
 PIONEER: Studies of Rare Pion Decays
 W. Altmannshofer¹, H. Rinnar², E. Blucher³, D. Reunanen^{4,5}, I. Caminata⁶

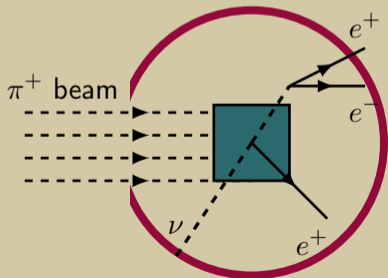


Experimental Capabilities

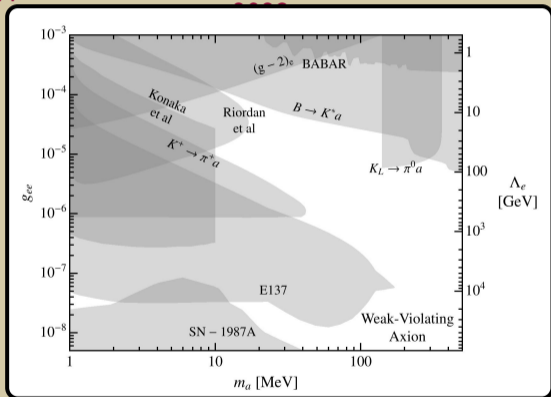
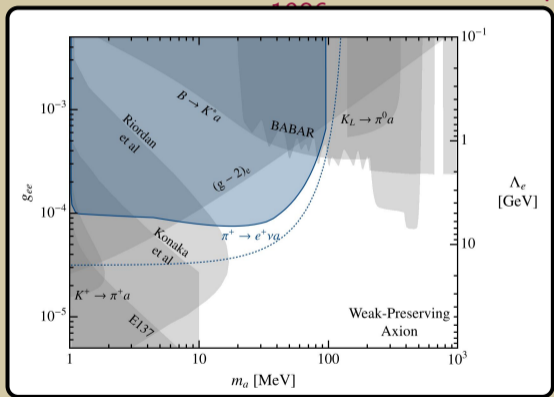


stringent even for weak-preserving!

PSI Ring Cyclotron Proposal R-22-01.1
 PIONEER: Studies of Rare Pion Decays
 W. Altmannshofer¹, H. Rinnar², E. Blucher³, D. Reunanen^{4,5}, I. Caminata⁶



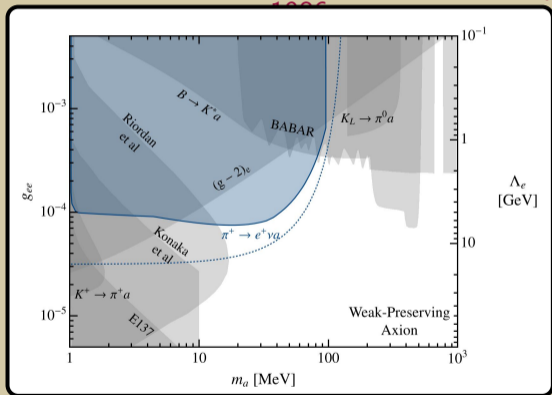
Experimental Capabilities



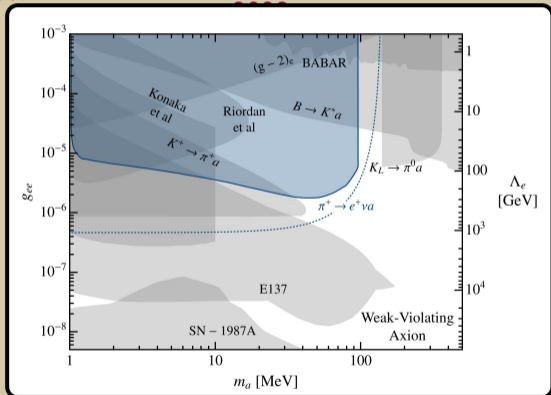
stringent even for weak-preserving!

Experimental Capabilities

time →

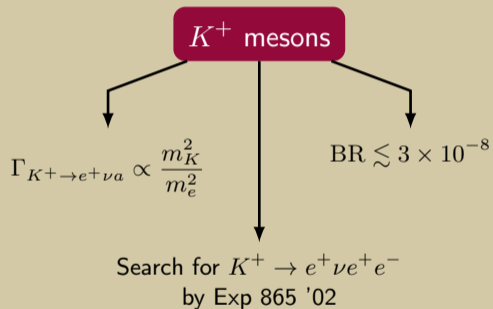


stringent even for weak-preserving!



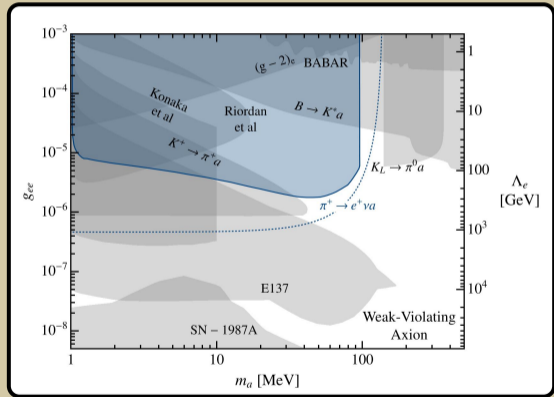
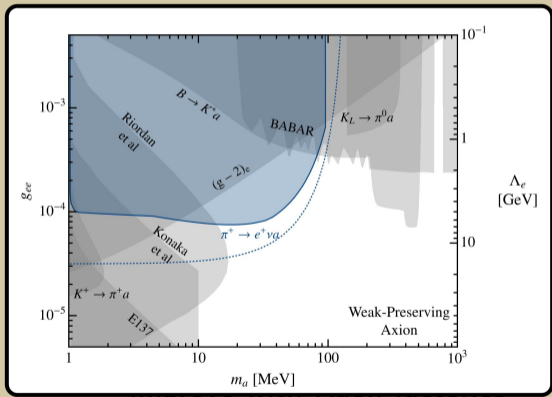
dramatically shapes parameter space!

Other Charged Mesons

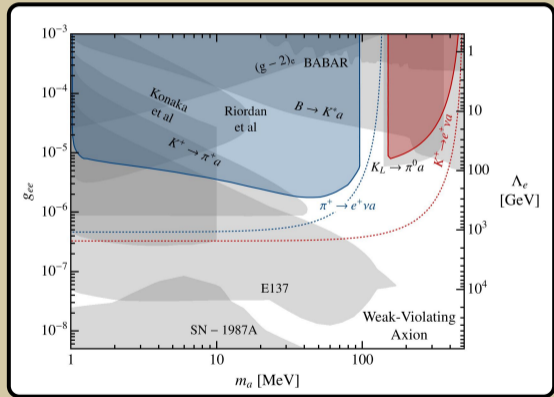
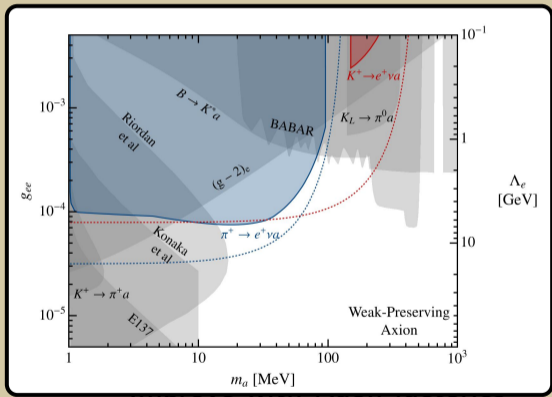


Improve with Kaon factories

Other Charged Mesons



Other Charged Mesons



Other Charged Mesons

K^+ mesons

$$\Gamma_{K^+ \rightarrow e^+ \nu e} \propto \frac{m_K^2}{m_e^2}$$

$$\text{BR} \lesssim 3 \times 10^{-8}$$

Search for $K^+ \rightarrow e^+ \nu e^+ e^-$
by Exp 865 '02

$D^+ / D_s^+ / B^+ / B_c^+$

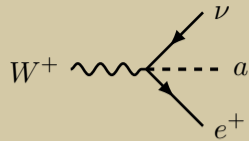
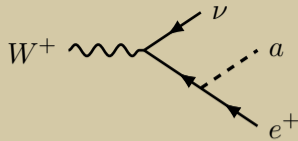
$$\Gamma_{M^+ \rightarrow e^+ \nu e} \propto \frac{m_M^2}{m_e^2}$$

$$\text{Need BR} = \mathcal{O}(10^{-6})$$

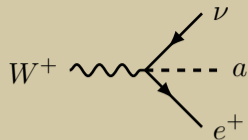
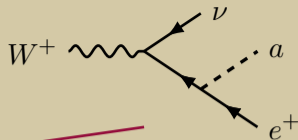
Large flavor-preserving
decays

Improve with Kaon factories

W^+ boson decay

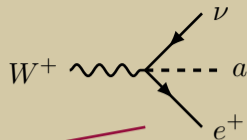
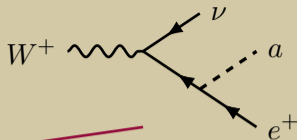


W^+ boson decay



$$\text{Br}(W^+ \rightarrow e^+ \nu a) \sim \left(\frac{g_{ee}}{0.1} \right)^2$$

W^+ boson decay

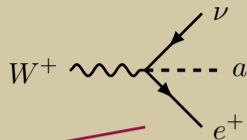
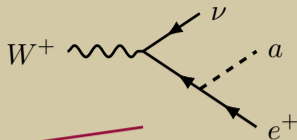


$$\propto \frac{m_W^2}{m_e^2}$$

$$\text{Br}(W^+ \rightarrow e^+ \nu a) \sim \left(\frac{g_{ee}}{0.1}\right)^2$$

$$\text{Br}(W^+ \rightarrow e^+ \nu a) \sim \left(\frac{g_{ee}}{10^{-3}}\right)^2$$

W^+ boson decay



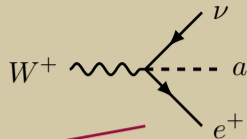
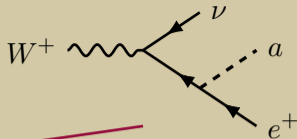
$$\propto \frac{m_W^2}{m_e^2}$$

$$\text{Br}(W^+ \rightarrow e^+ \nu a) \sim \left(\frac{g_{ee}}{0.1}\right)^2$$

$$\text{Br}(W^+ \rightarrow e^+ \nu a) \sim \left(\frac{g_{ee}}{10^{-3}}\right)^2$$

What is bound
on rare W -boson
decays?

W^+ boson decay



$$\propto \frac{m_W^2}{m_e^2}$$

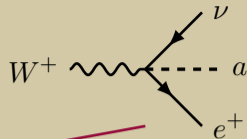
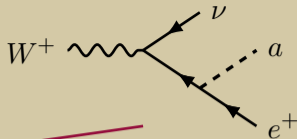
$$\text{Br}(W^+ \rightarrow e^+ \nu a) \sim \left(\frac{g_{ee}}{0.1} \right)^2$$

$$\text{Br}(W^+ \rightarrow e^+ \nu a) \sim \left(\frac{g_{ee}}{10^{-3}} \right)^2$$

What is 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



$$\propto \frac{m_W^2}{m_e^2}$$

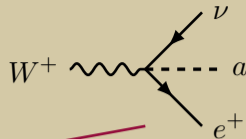
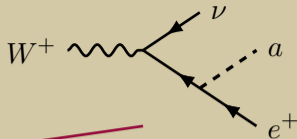
$$\text{Br}(W^+ \rightarrow e^+ \nu a) \sim \left(\frac{g_{ee}}{0.1}\right)^2$$

$$\text{Br}(W^+ \rightarrow e^+ \nu a) \sim \left(\frac{g_{ee}}{10^{-3}}\right)^2$$

What is 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 |
| $e^+ e^- \nu e^+$ | < ??? | | |

W^+ boson decay



$$\propto \frac{m_W^2}{m_e^2}$$

$$\text{Br}(W^+ \rightarrow e^+ \nu a) \sim \left(\frac{g_{ee}}{0.1}\right)^2$$

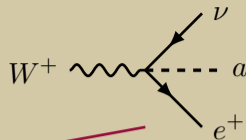
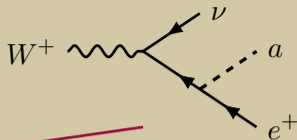
$$\text{Br}(W^+ \rightarrow e^+ \nu a) \sim \left(\frac{g_{ee}}{10^{-3}}\right)^2$$

What is 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 |
| $e^+ e^- \nu e^+$ | < ??? | | |

contribute to total width
2.085 ± 0.04 GeV

W^+ boson decay



$$\propto \frac{m_W^2}{m_e^2}$$

$$\text{Br}(W^+ \rightarrow e^+ \nu a) \sim \left(\frac{g_{ee}}{0.1}\right)^2$$

$$\text{Br}(W^+ \rightarrow e^+ \nu a) \sim \left(\frac{g_{ee}}{10^{-3}}\right)^2$$

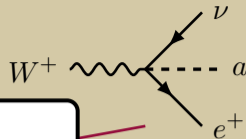
What is bound on rare W -boson decays?

| 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 |
| $e^+ e^- \nu e^+$ | < $\mathcal{O}(10^{-5})$ | | |

contribute to total width
2.085 ± 0.04 GeV

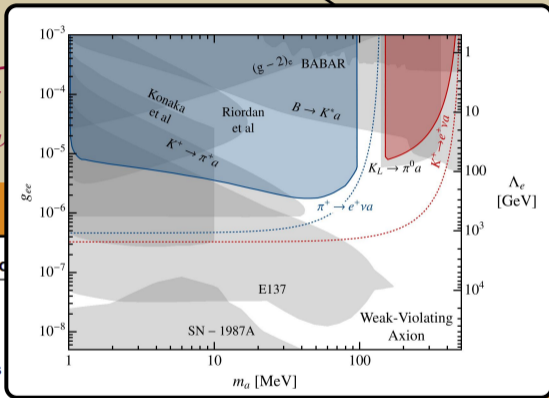
dedicated search?

W^+ boson decay



$$\propto \frac{m_W^2}{m_e^2}$$

$Br(W^+ \rightarrow e^+ \nu)$



What is bound on rare W -boson decays?

W^+ DECAY

$\ell^+ \nu$

$e^+ \nu$

$\mu^+ \nu$

$\tau^+ \nu$

hadrons

$\pi^+ \gamma$

$D_s^+ \gamma$

$c\bar{X}$

$c\bar{s}$

invisible

$\pi^+ \pi^+ \pi^-$

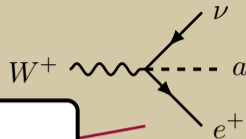
$e^+ e^- \nu e^+$

| | | | |
|--------------------------|------------------|-----|-------|
| < 1.3 | $\times 10^{-3}$ | 95% | 40165 |
| (33.3 ± 2.6) | % | - | - |
| $(31 \pm_{-11}^{+13})$ | % | - | - |
| [e] | (1.4 ± 2.9) | % | - |
| < 1.01 | $\times 10^{-6}$ | 95% | 40189 |
| $< \mathcal{O}(10^{-5})$ | | | |

contribute to total width
 2.085 ± 0.04 GeV

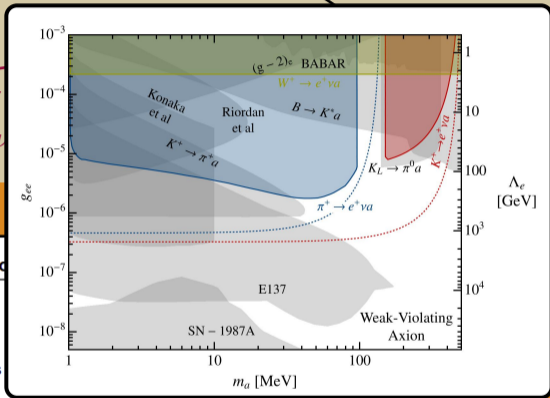
dedicated search?

W^+ boson decay



$$\propto \frac{m_W^2}{m_e^2}$$

$Br(W^+ \rightarrow e^+ \nu)$



What is bound on rare W -boson decays?

W^+ DEC

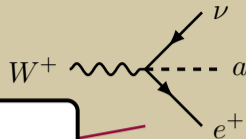
- $\ell^+ \nu$
- $e^+ \nu$
- $\mu^+ \nu$
- $\tau^+ \nu$
- hadrons
- $\pi^+ \gamma$
- $D_s^+ \gamma$
- cX
- $c\bar{s}$
- invisible
- $\pi^+ \pi^+ \pi^-$
- $e^+ e^- \nu e^+$

| | | | |
|--------------------------|------------------|-----|-------|
| < 1.3 | $\times 10^{-3}$ | 95% | 40165 |
| (33.3 ± 2.6) | % | - | - |
| $(31 \pm_{-11}^{+13})$ | % | - | - |
| [e] | (1.4 ± 2.9) | % | - |
| < 1.01 | $\times 10^{-6}$ | 95% | 40189 |
| $< \mathcal{O}(10^{-5})$ | | | |

contribute to total width
 2.085 ± 0.04 GeV

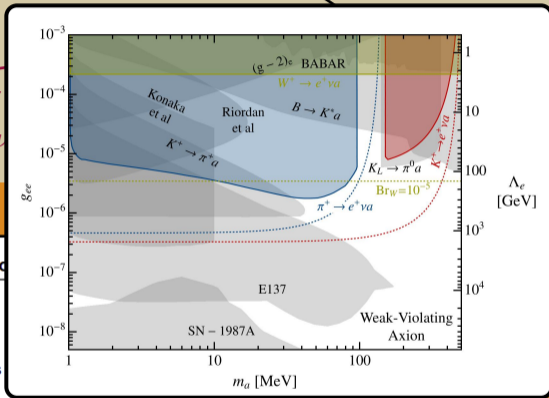
dedicated search?

W^+ boson decay



$$\propto \frac{m_W^2}{m_e^2}$$

$Br(W^+ \rightarrow e^+ \nu)$



What is bound on rare W -boson decays?

W^+ DEC

- $\ell^+ \nu$
- $e^+ \nu$
- $\mu^+ \nu$
- $\tau^+ \nu$
- hadrons
- $\pi^+ \gamma$
- $D_s^+ \gamma$
- cX
- $c\bar{s}$
- invisible
- $\pi^+ \pi^+ \pi^-$
- $e^+ e^- \nu e^+$

| | | | |
|--------------------------|------------------|-----|-------|
| < 1.3 | $\times 10^{-3}$ | 95% | 40165 |
| (33.3 ± 2.6) | % | - | - |
| $(31 \pm_{-11}^{+13})$ | % | - | - |
| [e] | (1.4 ± 2.9) | % | - |
| < 1.01 | $\times 10^{-6}$ | 95% | 40189 |
| $< \mathcal{O}(10^{-5})$ | | | |

contribute to total width
 $2.085 \pm 0.04 \text{ GeV}$

dedicated search?

Proton Beam Dump Experiments

Ex: CHARM experiment

proton
source

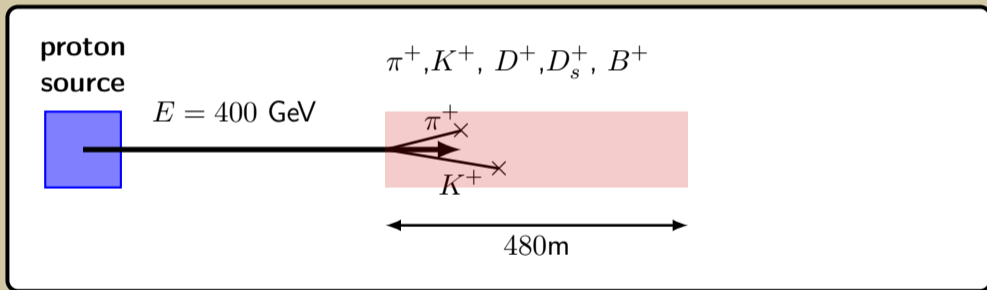


$E = 400 \text{ GeV}$



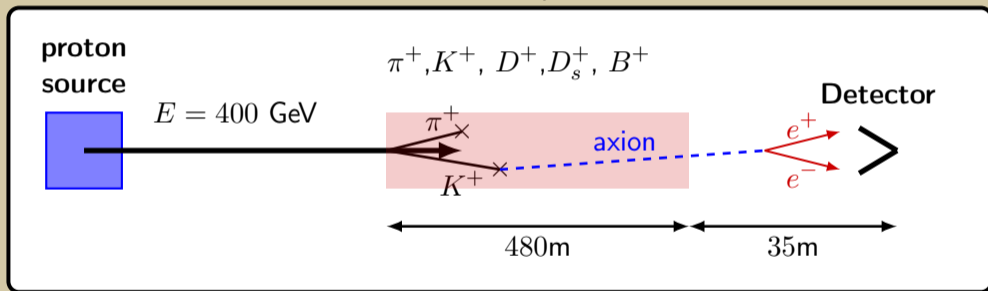
Proton Beam Dump Experiments

Ex: CHARM experiment



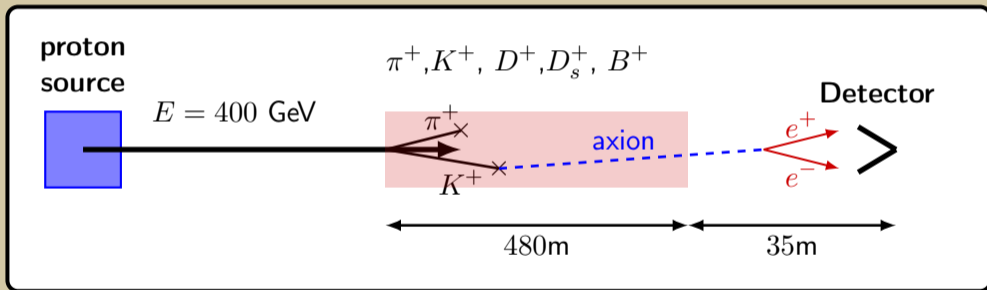
Proton Beam Dump Experiments

Ex: CHARM experiment



Proton Beam Dump Experiments

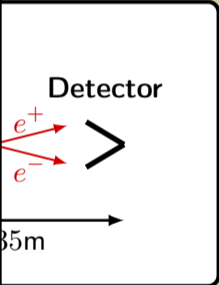
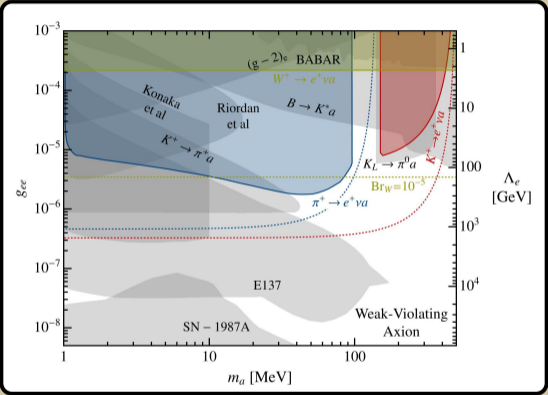
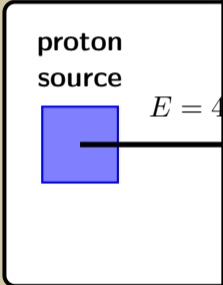
Ex: CHARM experiment



first use of
 D, D_s, B_c mesons

observed zero
events [CHARM - 1985]

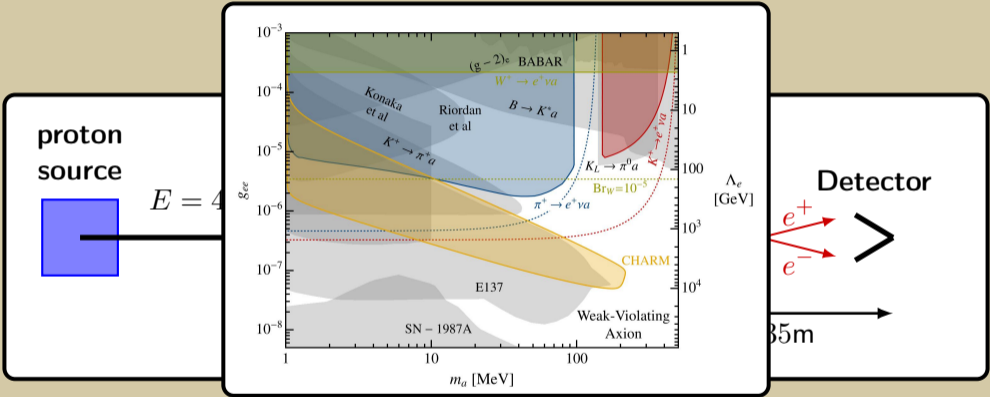
Proton Beam Dump Experiments



first use of
 D, D_s, B_c mesons

observed zero
events [CHARM - 1985]

Proton Beam Dump Experiments



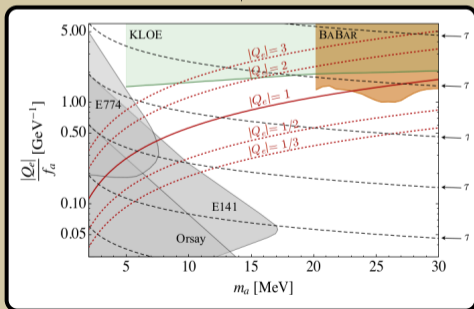
first use of
 D, D_s, B_c mesons

observed zero
events [CHARM - 1985]

Weak-Preserving Implications

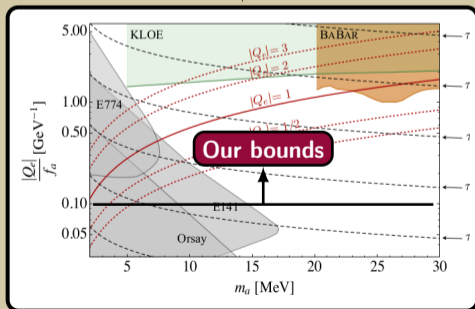
Weak-Preserving Implications

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



Weak-Preserving Implications

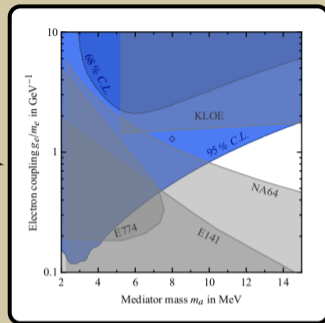
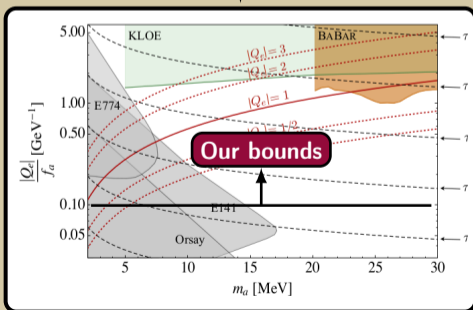
[Alves, Weiner - '17] , [Alves - '21]
revisited possibility of
MeV QCD axion



Weak-Preserving Implications

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

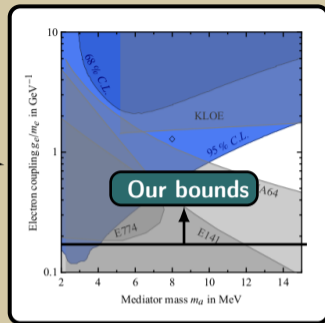
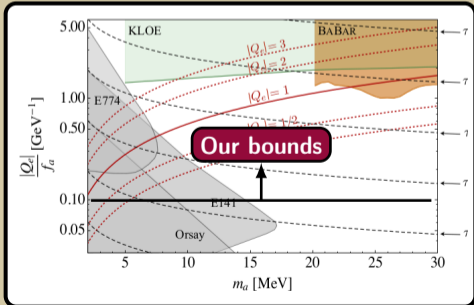
[Buttazzo et al - '21]
propose ALP mediate
Xenon-1T excess



Weak-Preserving Implications

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

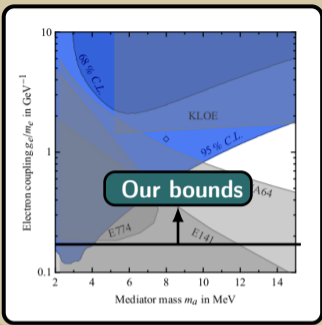
[Buttazzo et al - '21]
propose ALP mediate
Xenon-1T excess



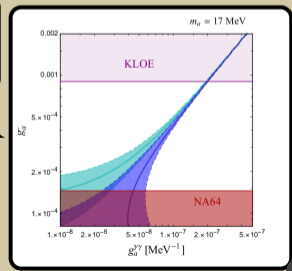
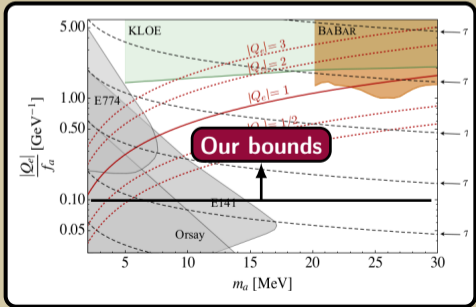
Weak-Preserving Implications

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

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



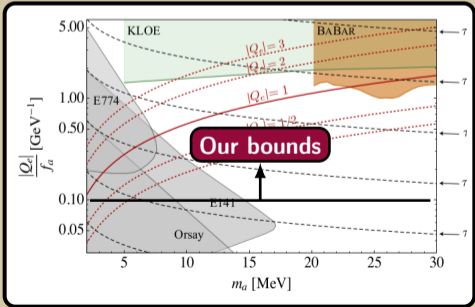
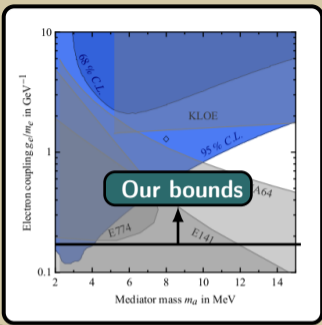
[Liu, McGinnis, Wagner, Wan - '21], ALP for Atomki excess



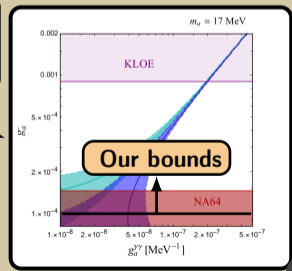
Weak-Preserving Implications

[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 axion-lepton interactions

weak-violating



need to
distinguish



weak-preserving

Summary

Revisited theory of axion-lepton interactions

weak-violating

need to
distinguish

weak-preserving

strong bounds in either case

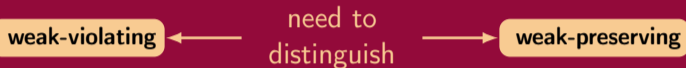
charged meson
decays

W boson
decays

proton beam
dumps

Summary

Revisited theory of axion-lepton interactions



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?**