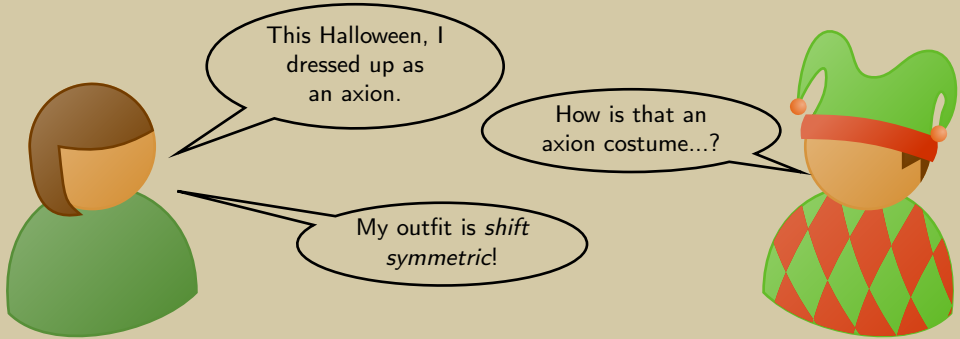
New Insights Into Axion-Lepton Interactions

Bay Area Particle Theory Seminar

[2209.00665] Altmannshofer, JD, and Gori

Jeff Dror



Outline

Introduction to Lepton-Axion Interactions

Lagrangian reformulation

New set of detection strategies

Implications

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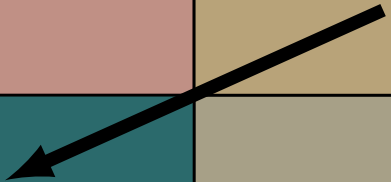

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Leptophilic Effective Theory

Shift symmetry:

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

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- Convenient normalization
- Vector coupling
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Claims in the literature

"The vector coupling is unphysical"

"The neutrino coupling is suppressed by m_ν"

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

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

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

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

- PQ charges are EW-symmetric
- Two parameters
- Benchmark model:

$$j^\mu_{\rm PQ} = \frac{g_{ee}}{m_e}\bar{e}\gamma_\mu P_R e$$ "DFSZ-like"

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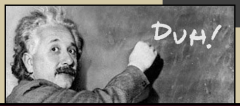

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$j^{\mu}_{\mathrm{PQ}} = \frac{g_{ee}}{m_e}\bar{e}\gamma_\mu P_R e$ "DFSZ-like"

- Generated through RG flow
- Also by $\partial^\mu a(HL)^\dagger\gamma_\mu(HL)$
- Benchmark model

$j^{\mu}_{\mathrm{PQ}} = \frac{g_{ee}}{2m_e}\bar{e}\gamma_\mu\gamma_5 e$ "KSVZ-like"

Requirement has dramatic consequences

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

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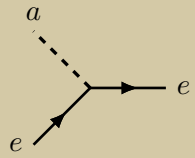
"Standard" form



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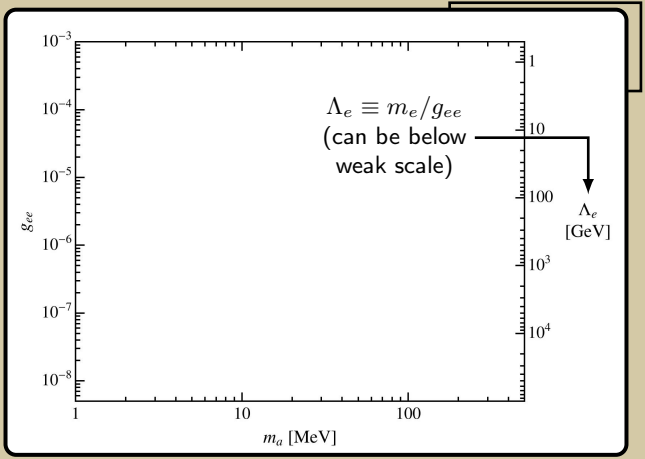

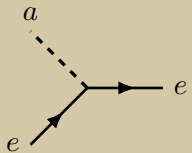

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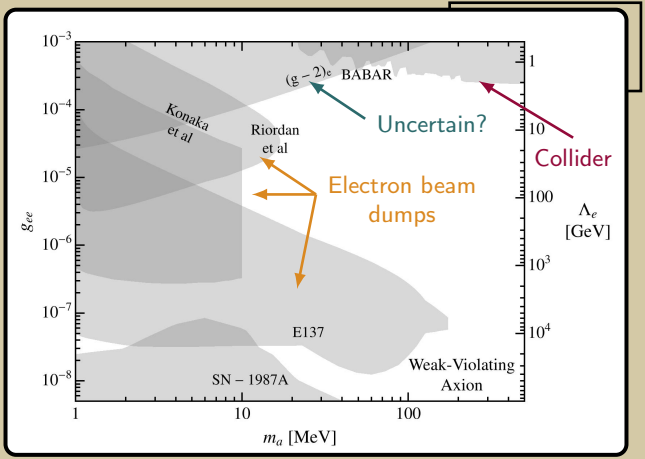

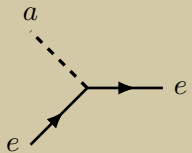

[**BABAR** - '14] , [**Riordan et al** - '87] , [**Bjorken et al** - '88], [**Bross et al** - '91]
[**Morel et al** - '20], [**Lucente, Carenza** - '21]

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

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

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

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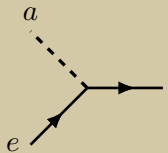
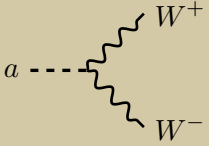


Anomaly terms



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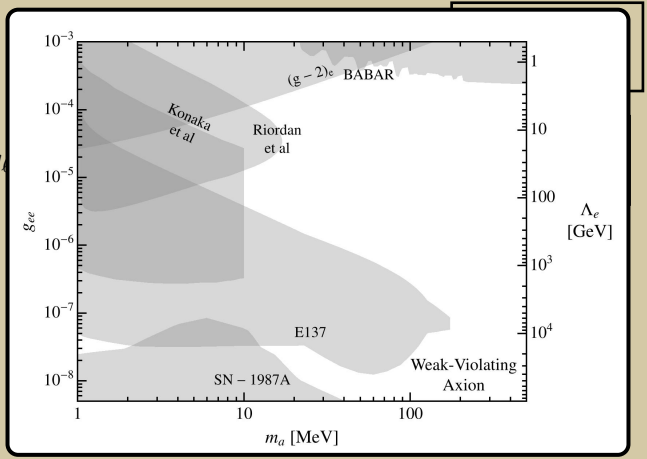

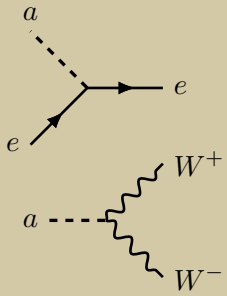

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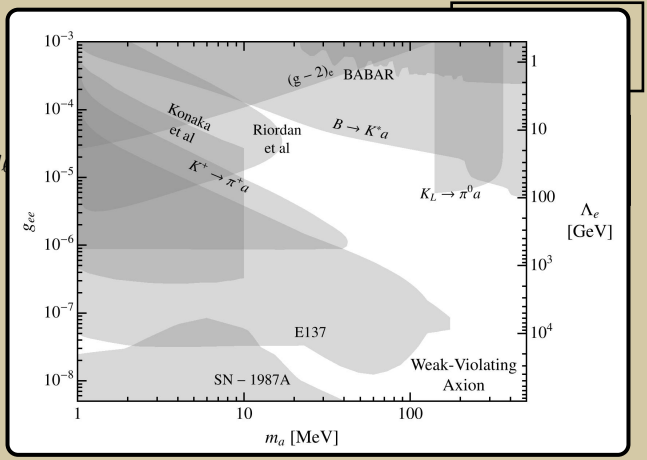
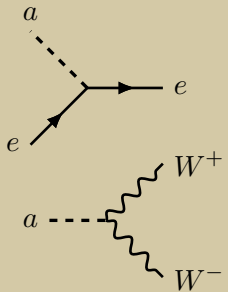


[**Bauer et al** - '21]



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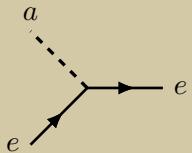

$$-\frac{1}{64\pi^2}\frac{1}{m_\ell}(g_{\ell\ell} - \bar{g}_{\ell\ell} - g_{\nu_\ell}) g^2 W^+_{\mu\nu}\tilde{W}^{-\,\mu\nu} + \dots$$

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

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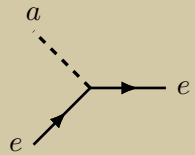

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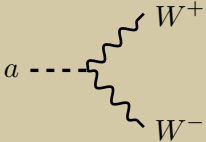

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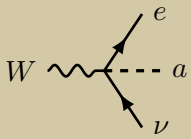


This work:

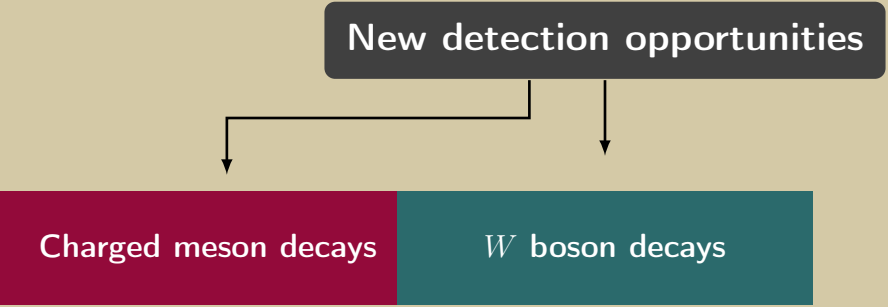
1. Importance of weak vertex
2. New bound on standard vertex

New detection opportunities

New detection opportunities

Charged meson decays

Relevant for all ALPs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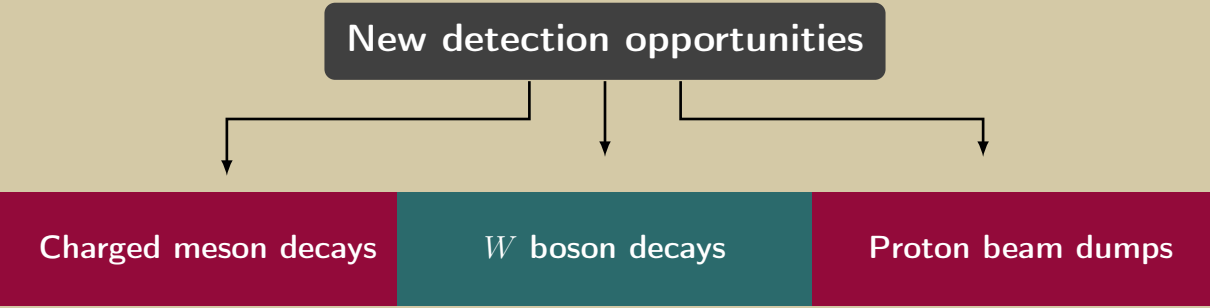
Relevant for weak-violating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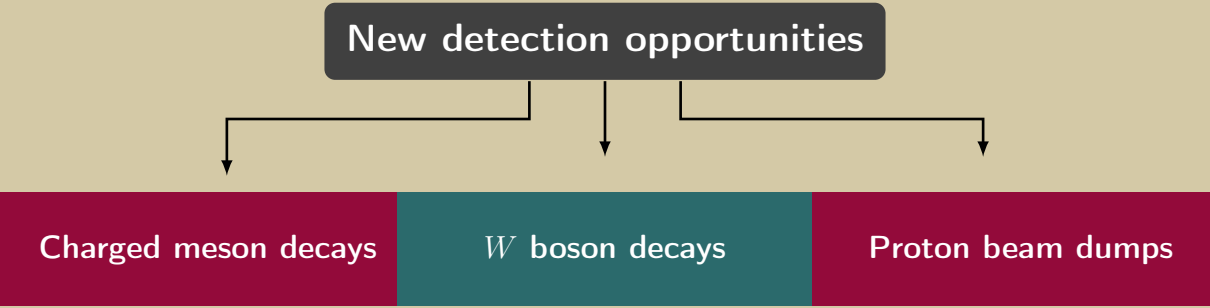
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Focus on electron coupling

ALPs from π^+ decay*

*ALP-π^0 mixing and quark coupling

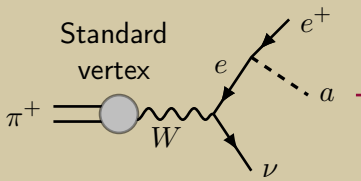
E.g., [**Krauss, Wise** - '86], [**Bardeen et al** - '87], [**Altmannshofer et al** - 19]

ALPs from π^+ decay*

Weak-preserving

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

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



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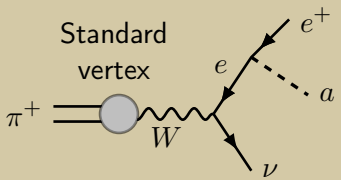

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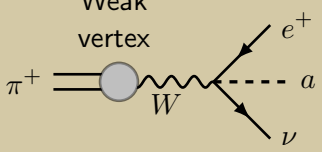

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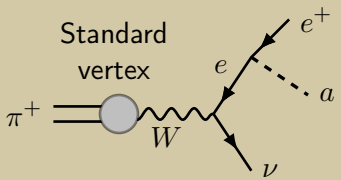

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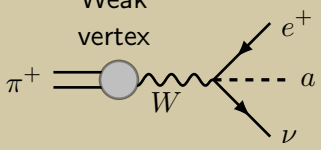
Detectable

Weak-violating



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Experimental Capabilities

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

SINDRUM Collaboration

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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]

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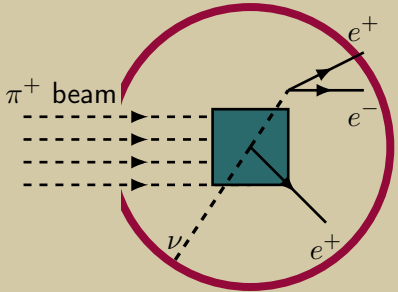

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π^+

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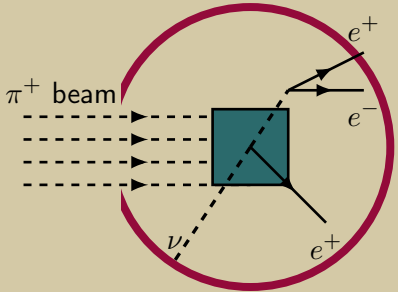
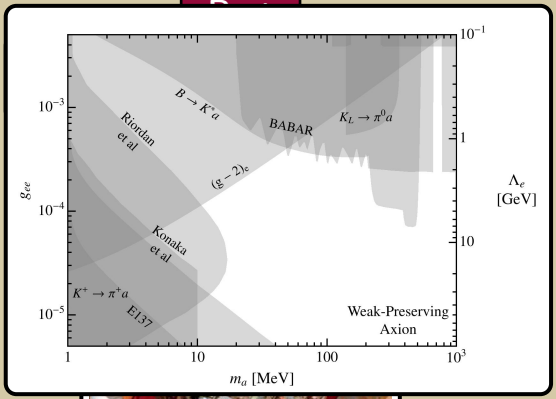


↳ Reach $\mathrm{Br}_{\pi^+\to e^+\nu a} \lesssim 10^{-11}$?

Experimental Capabilities



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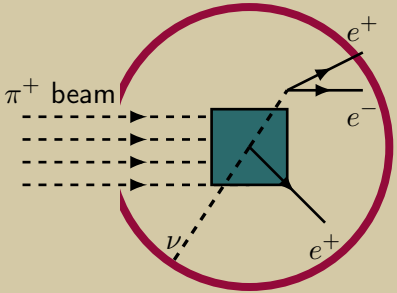

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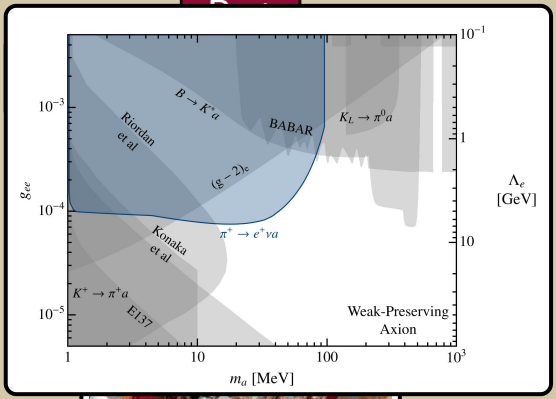
Experimental Capabilities



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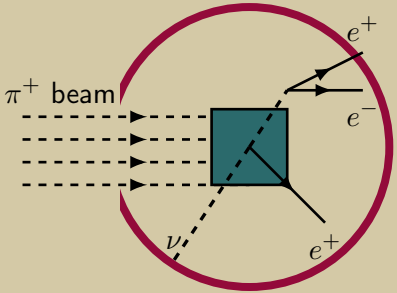
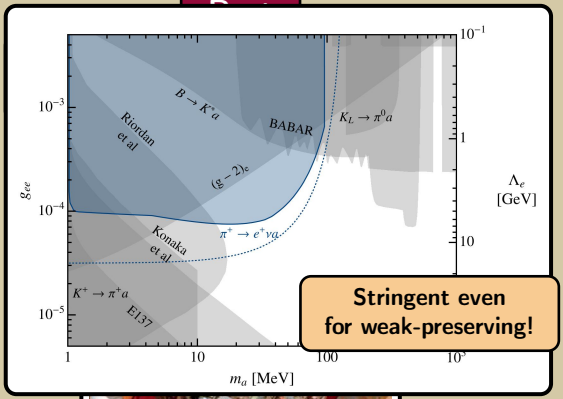
PSI Ring Cyclotron Proposal R-22-01.1
PIONEER: Studies of Rare Pion Decays

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



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

Future

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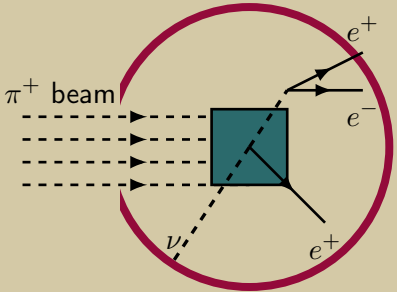

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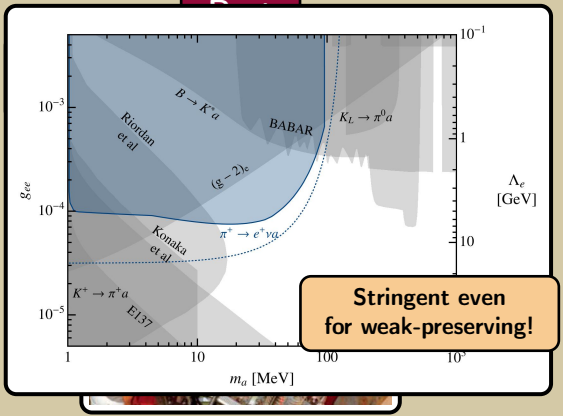

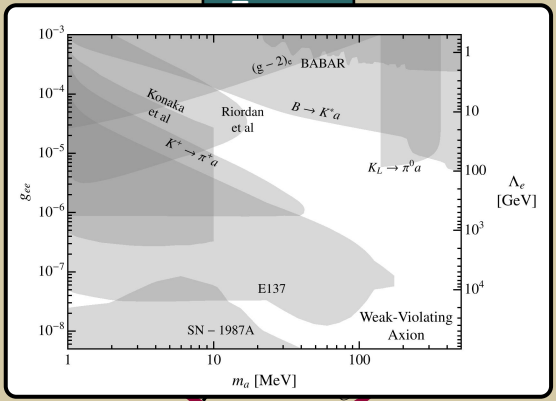

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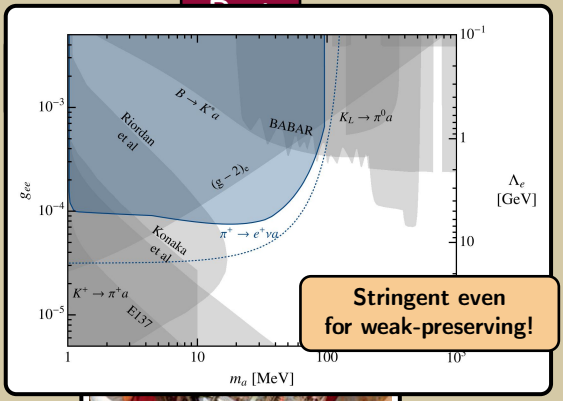
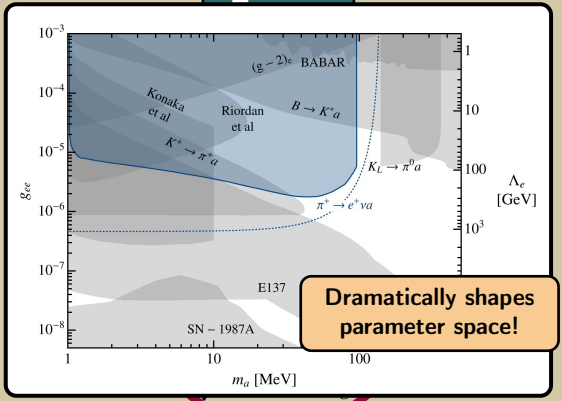


Stringent even for weak-preserving!



Dramatically shapes parameter space!

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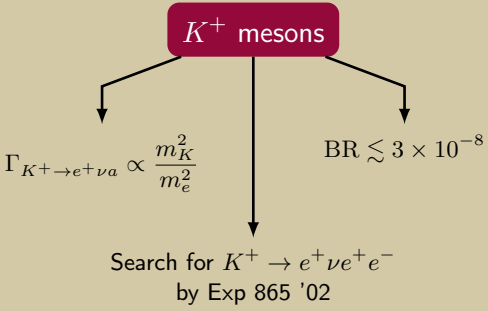
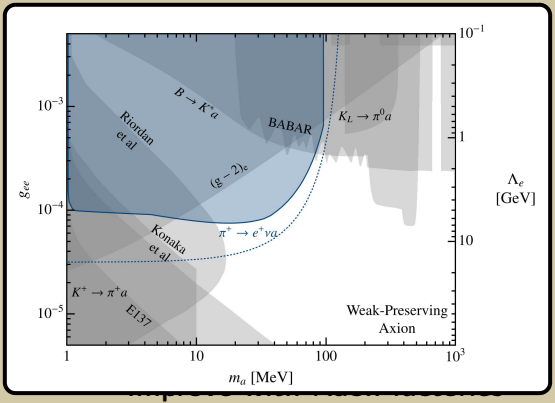
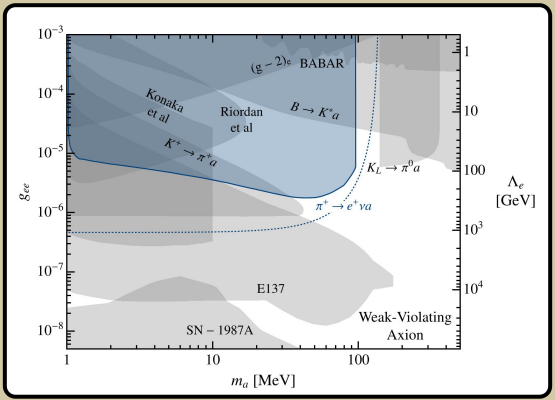
Other charged mesons



Improve with Kaon factories

Other charged mesons





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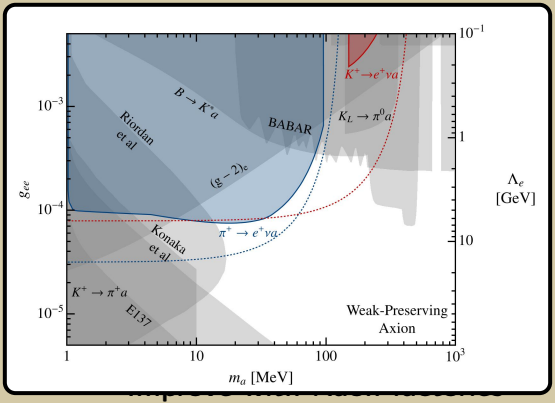

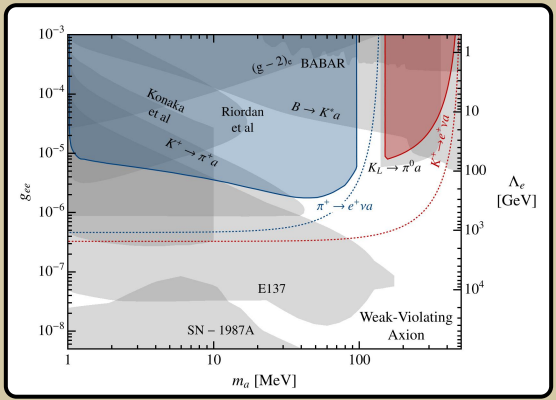

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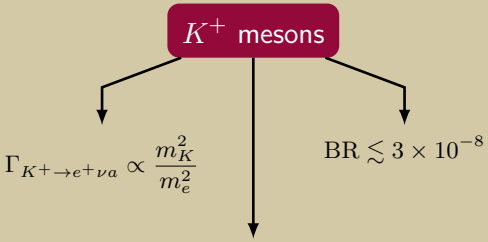
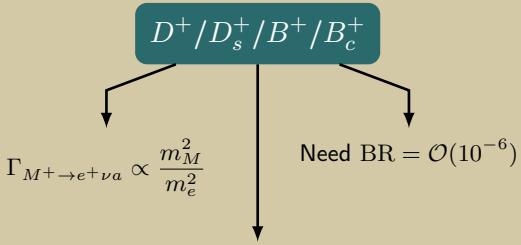
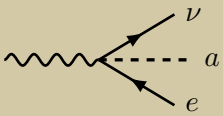




Improve with Kaon factories

W^+ boson decay



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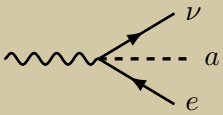
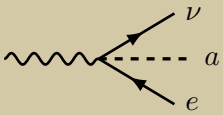


W boson decay width $\propto m_W^2/m_e^2$ for weak-violating ALP

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

Irrelevant for weak-preserving

W^+ boson decay



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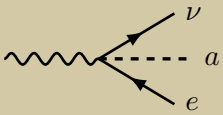
Bound on rare W-boson decays?

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



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↳ Contribute to total width,

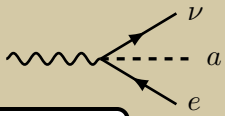
$$\Gamma_W = 2.085 \pm 0.04 \text{ GeV}$$

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

↳ Dedicated search:

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

W^+ boson decay



W boson decay width for weak-violatin

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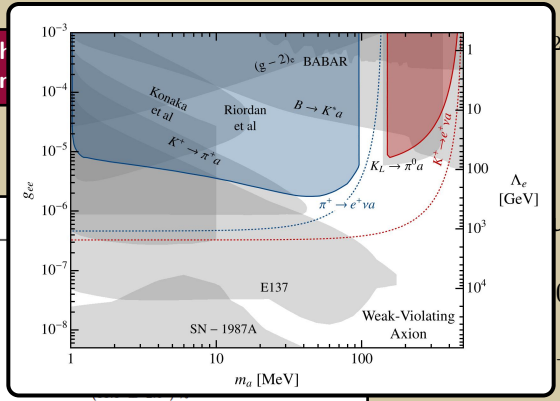

W+ DECAY MODES

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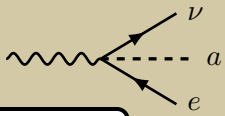

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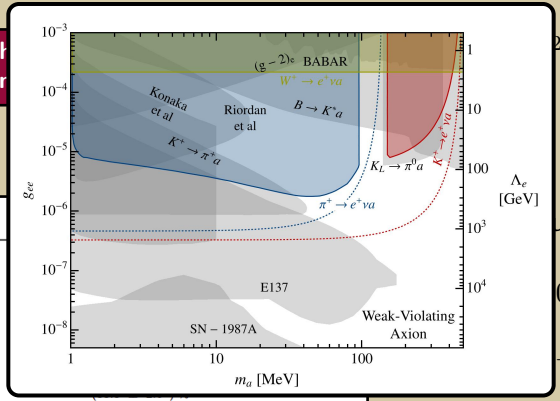

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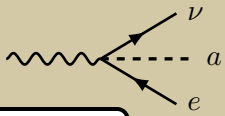

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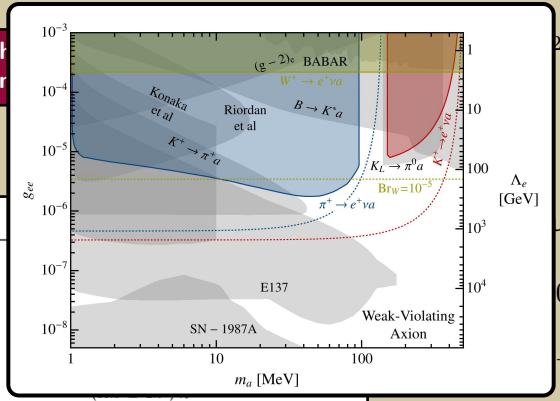

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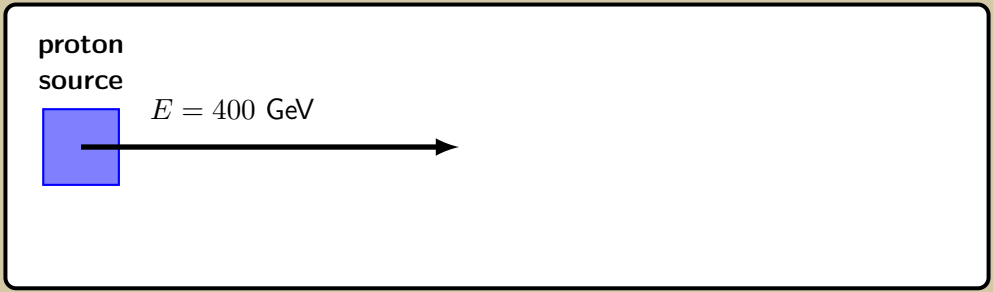
Proton beam dump experiments

Ex: CHARM experiment



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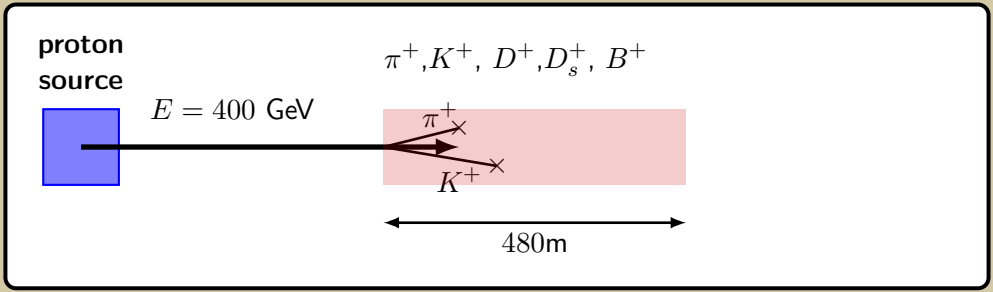

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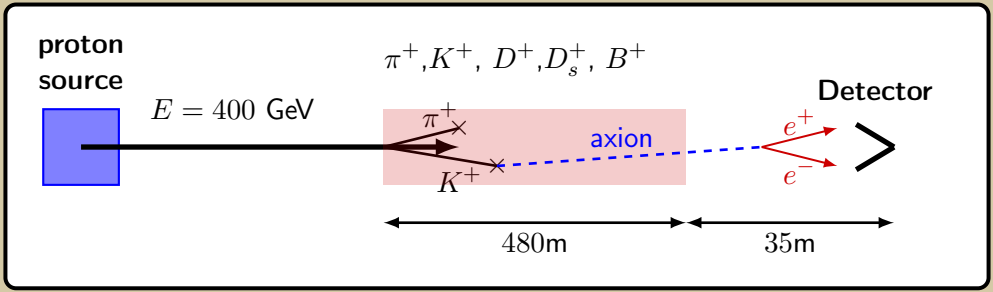

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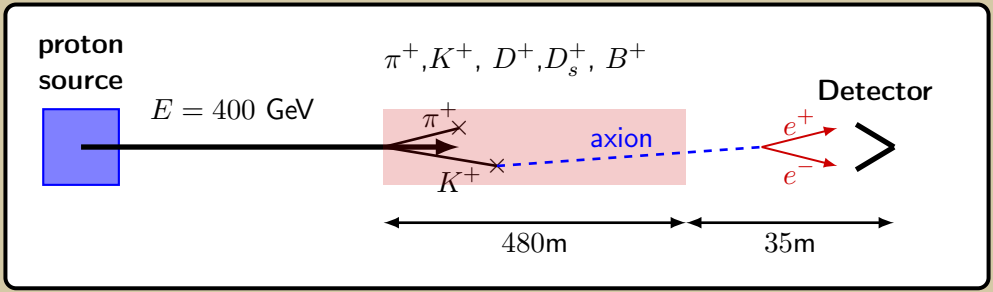


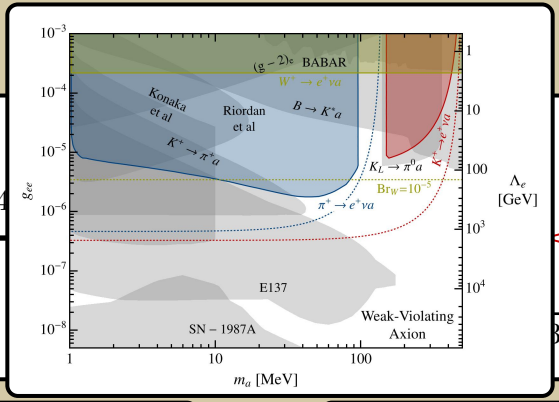
First use of D, D_s, B_c mesons

Observed zero events [CHARM - 1985]

Proton beam dump experiments

proton source

$E = 4$



Detector

e^+

e^-

35m

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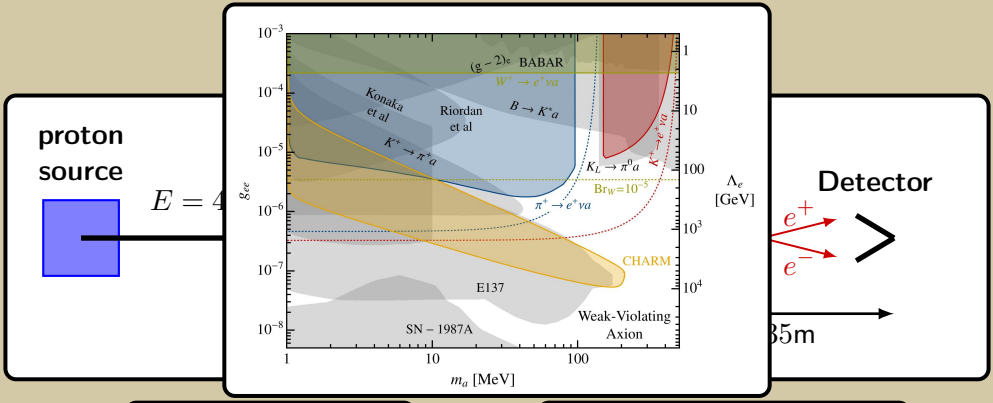

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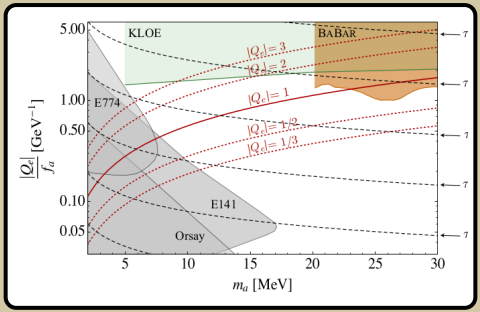
[Alves, Weiner - '17] , [Alves - '21] revisited possibility of MeV QCD axion



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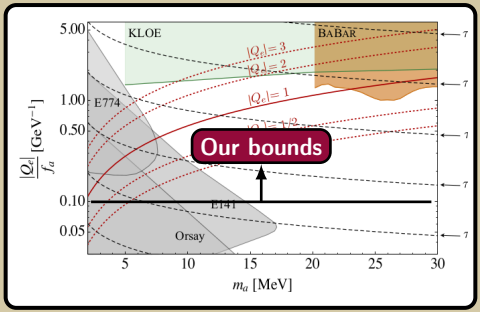

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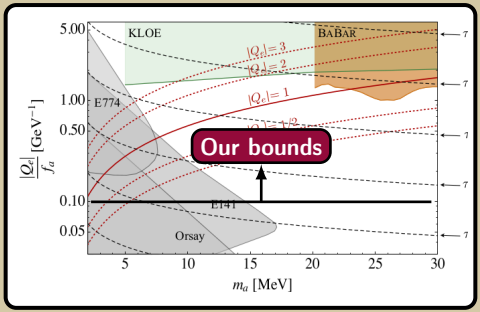
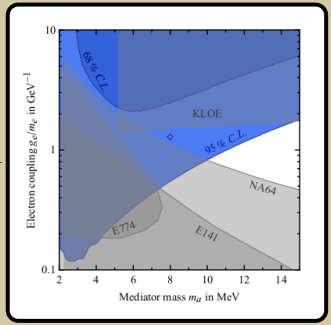


[Buttazzo et al - '21] propose ALP mediate Xenon-1T excess



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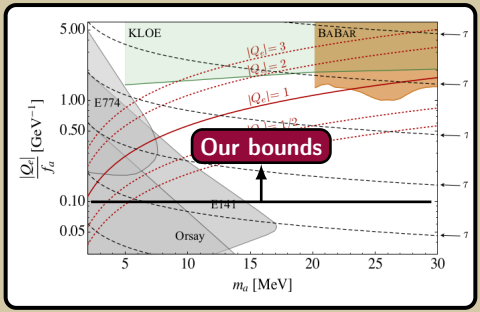

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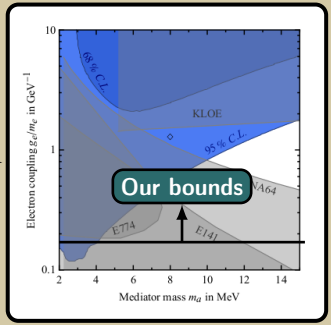

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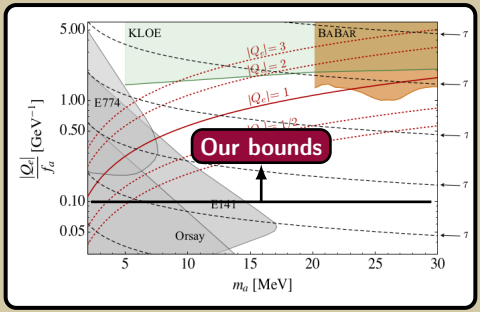

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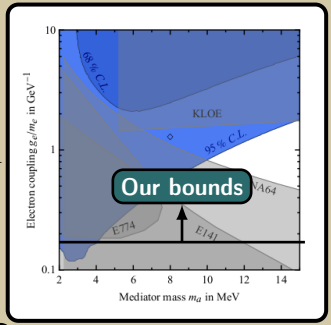
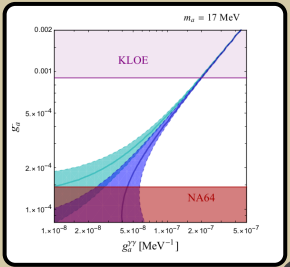


[Liu, McGinnis, Wagner, Wan - '21], ALP for Atomki excess



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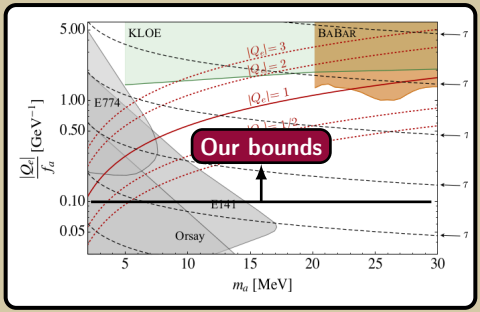

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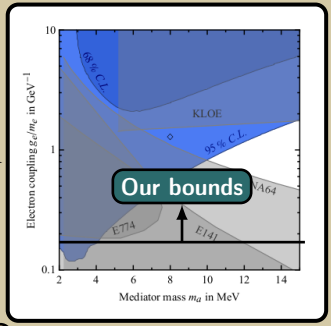

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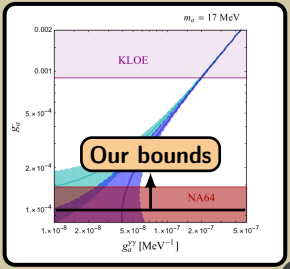

Summary

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

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Final musings

Weak-violating ALPs drive new phenomenology

Every model has some weak-violation. Implications?