Leptophilic ALPs

Oklahoma State University

Jeff Dror

To appear,
Altmannshofer, JD, and Gori

$e^{\pm}, \nu_e$

$\mu^{\pm}, \nu_\mu$

$\tau^{\pm}, \nu_\tau$

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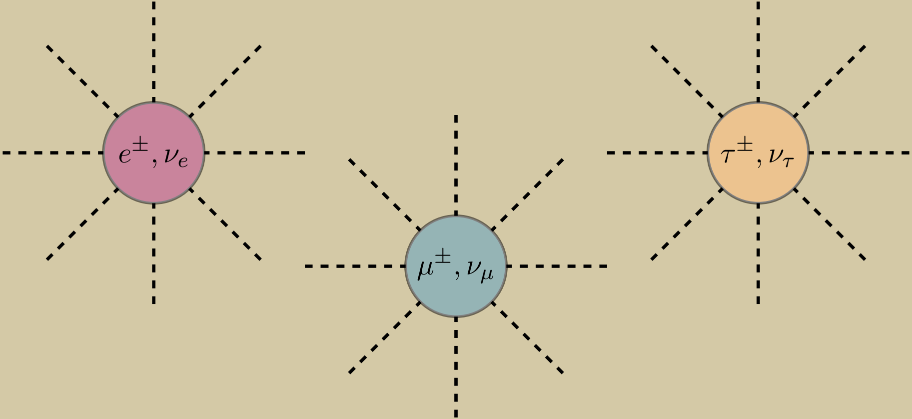
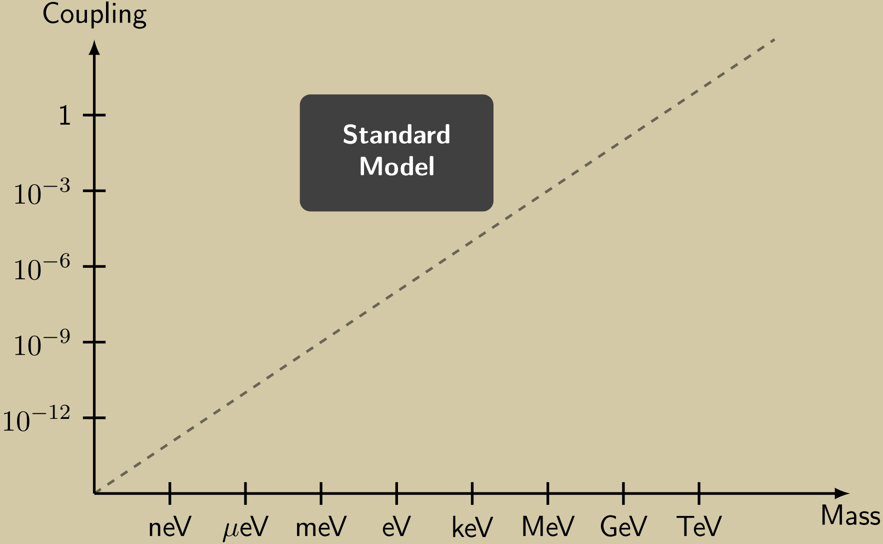


New particles meet experiment



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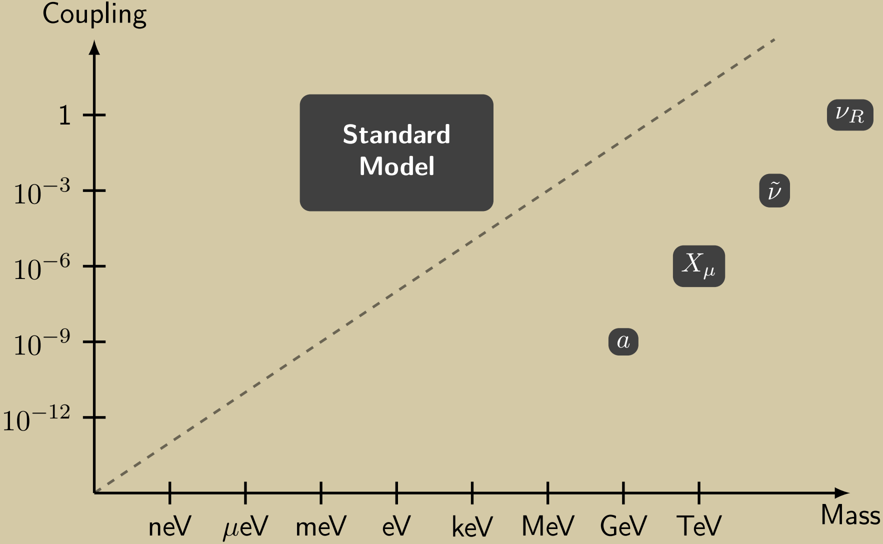

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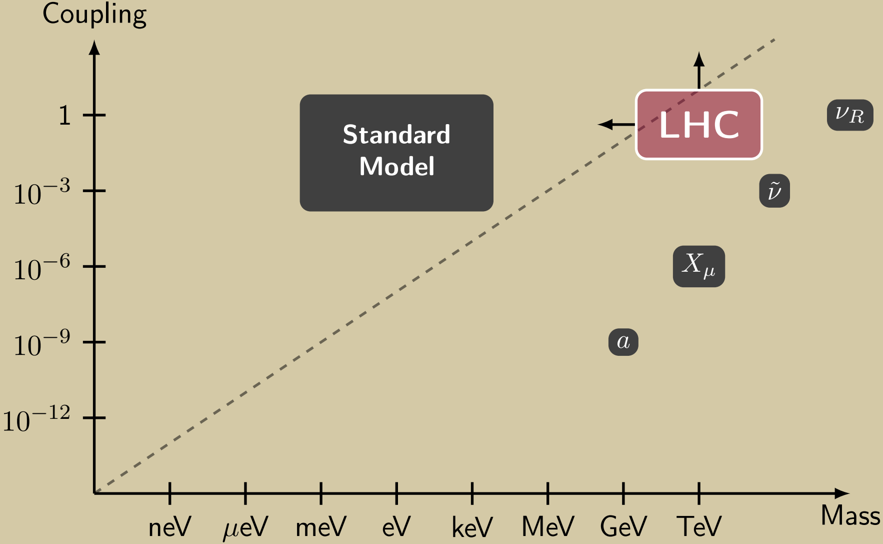

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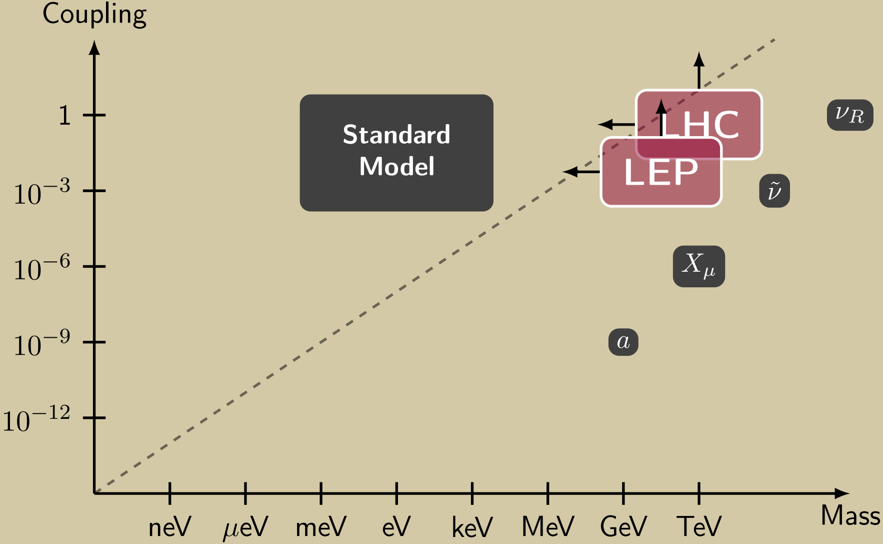

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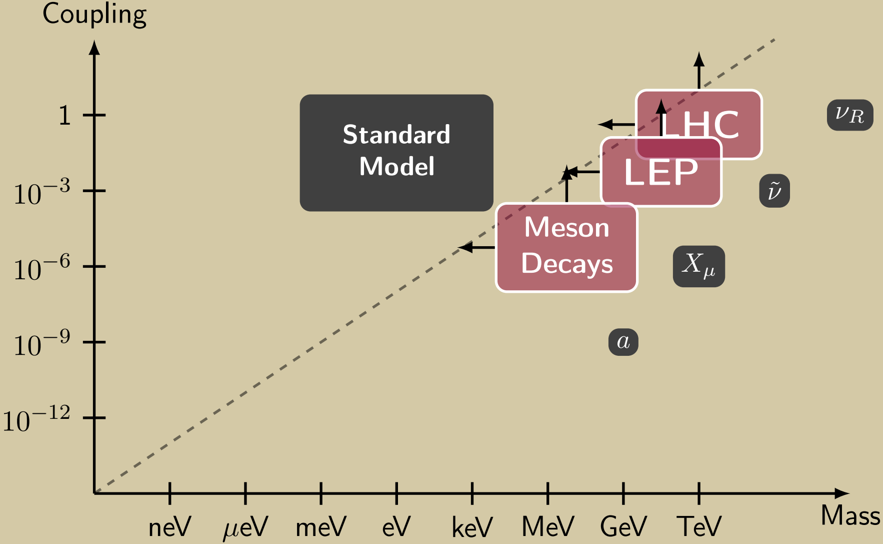

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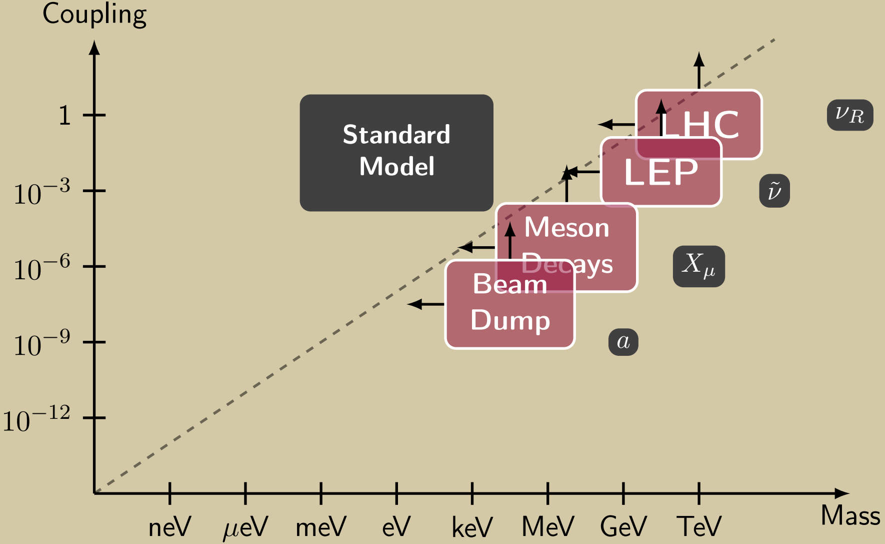

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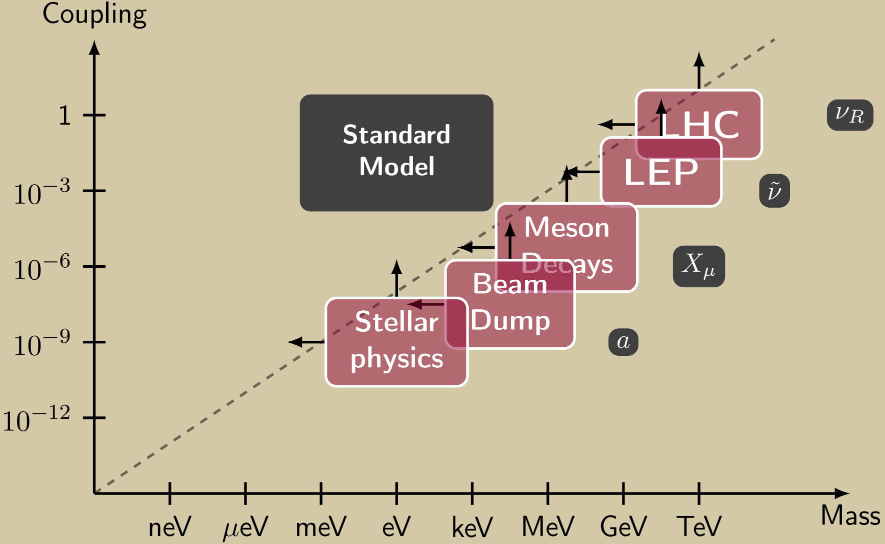

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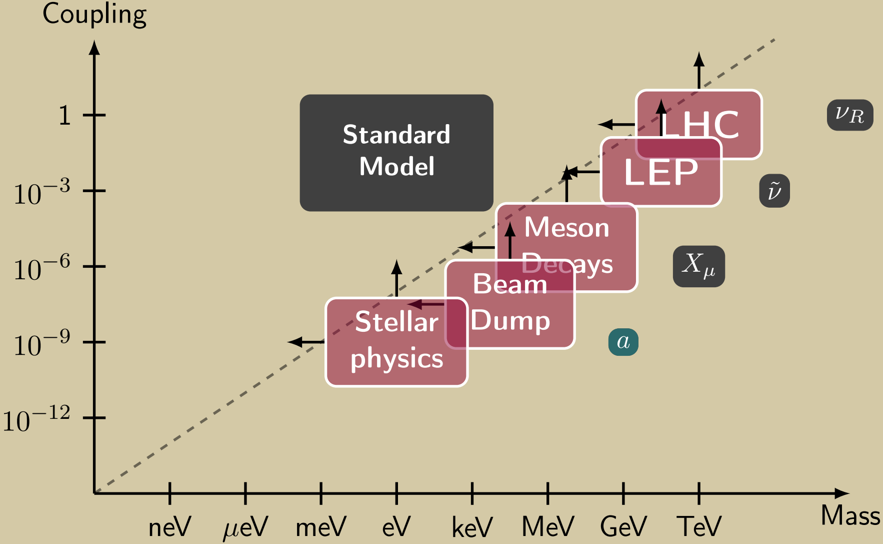

Outline

Introduction to Axion-like Particles (ALPs)

Theoretical subtleties and Lagrangian reformulation

New set of detection strategies

Implications

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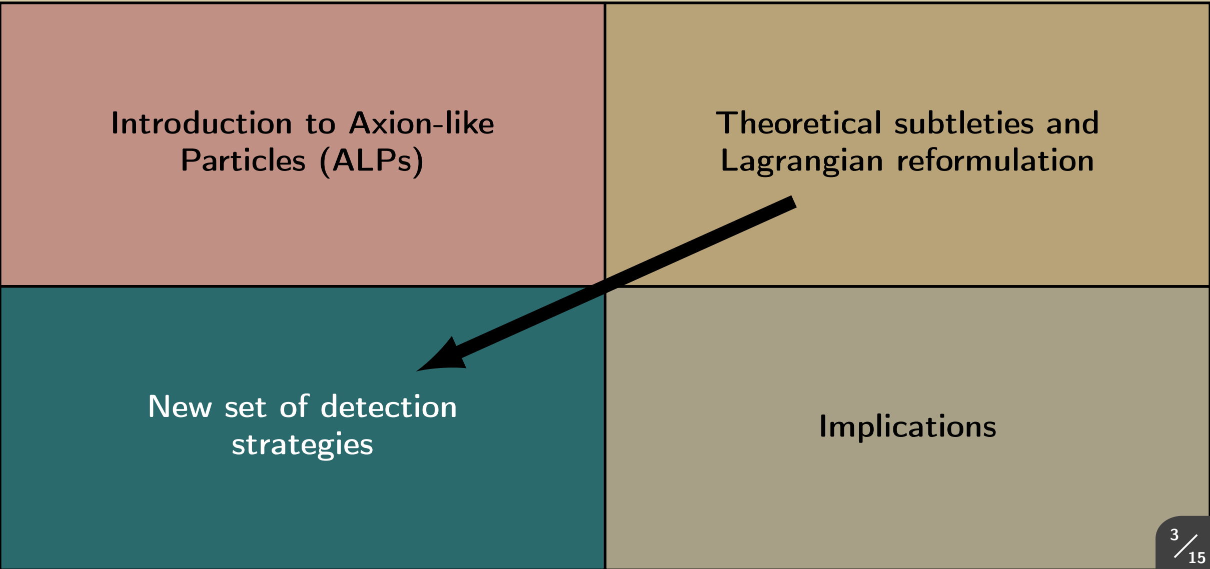

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Who
What
Where
~~When~~
Why

What is an ALP? → **Light** scalar
with approximate
shift symmetry

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Why are there ALPs?

→ Strong CP problem

→ Explain experimental anomalies

→ String Theory?

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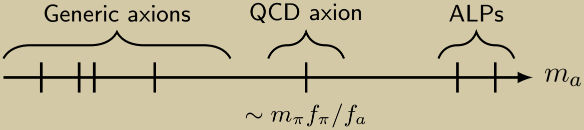

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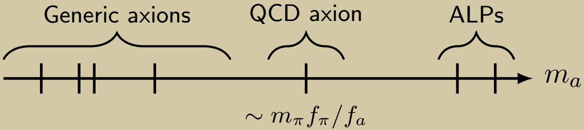
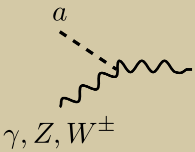
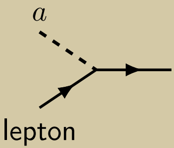
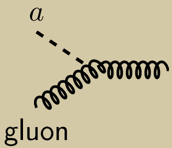
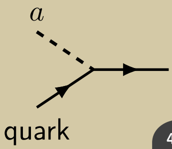


Who do ALPs interact with?









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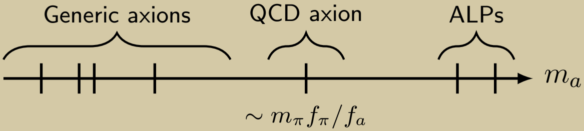

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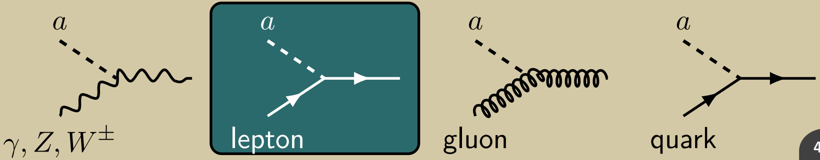

Leptophilic Effective Theory

Shift symmetry:

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

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Convenient normalization

Vector coupling

Axial-vector coupling

Neutrino coupling

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Claims in the literature

"The vector coupling is unphysical"

"The neutrino coupling is suppressed by m_ν"

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

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Majoron:	$\bar{g}_{\ell\ell} = g_{\nu_\ell}$,	$g_{\ell\ell} = 0$
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- PQ charges are EW-symmetric
- Two parameters
- Benchmark model:

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Whether or not this is required has dramatic consequences

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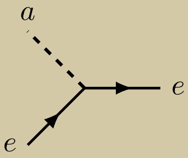
“Standard” form



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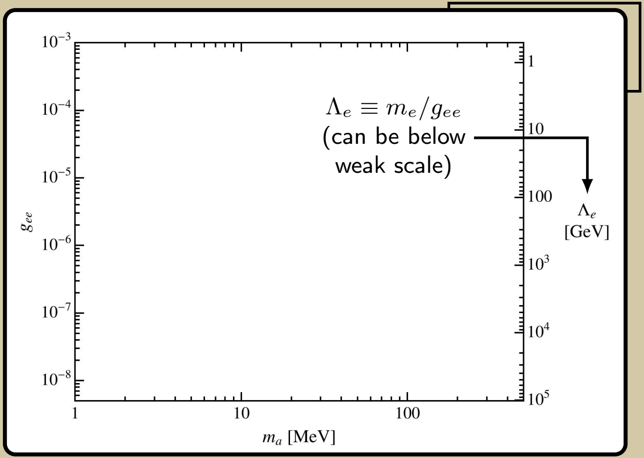
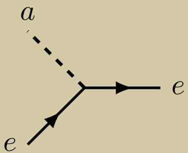


$\Lambda_e \equiv m_e/g_{ee}$

(can be below weak scale)



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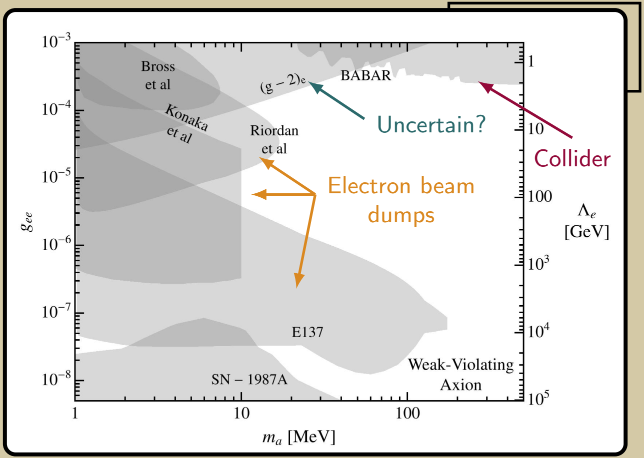
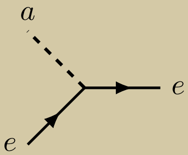


Uncertain?

Collider

Electron beam dumps



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

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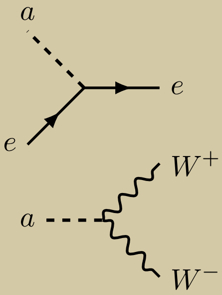
"Standard" form

Anomaly terms



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

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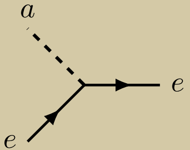

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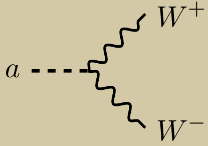

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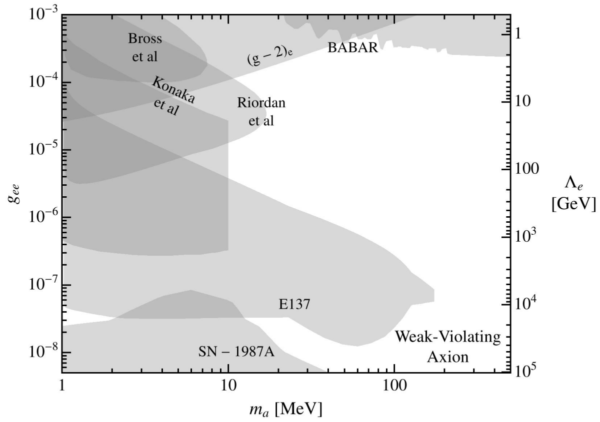

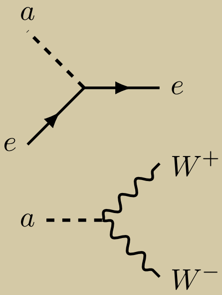

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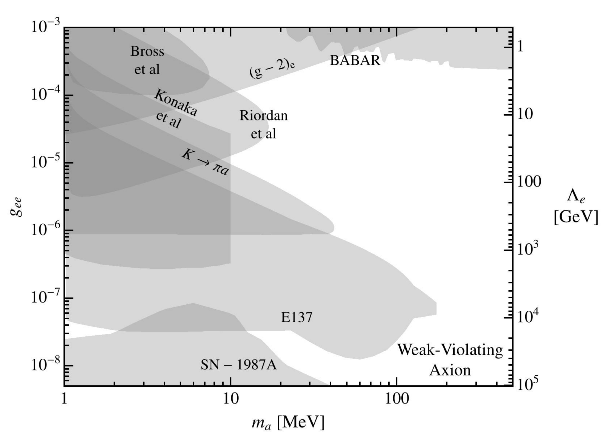
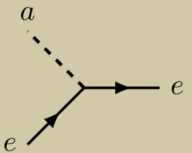
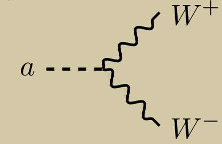


[Bauer et al - '21]





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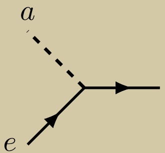

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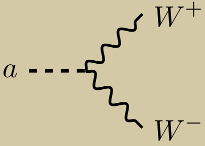

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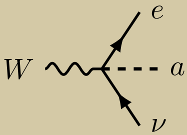
Weak vertex



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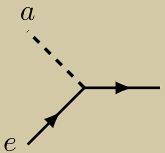
$\propto 1/m_\ell!$

“Standard” form



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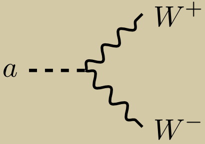

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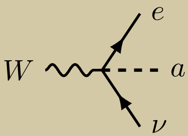

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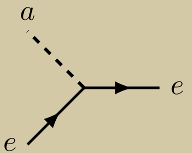

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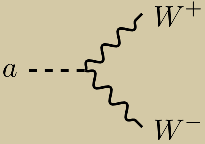
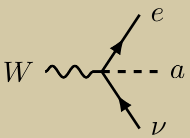


Weak vertex



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

New detection opportunities

Charged meson decays

W boson decays

Proton beam dumps

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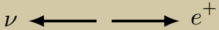
Relevant for weak-violating

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]

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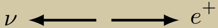

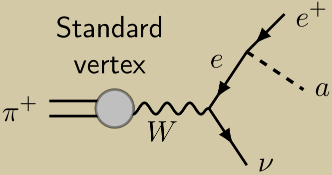

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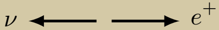

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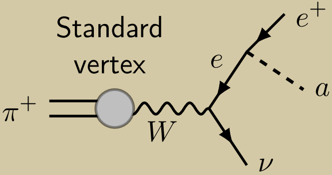
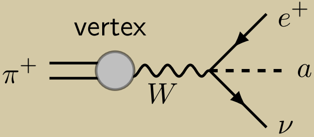


Weak vertex



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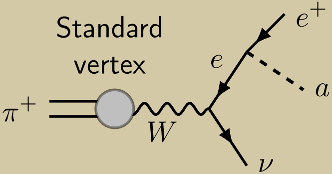

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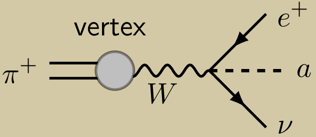

Weak-preserving

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

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

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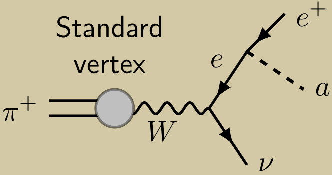

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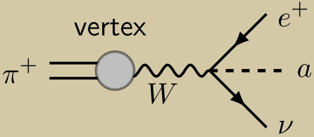

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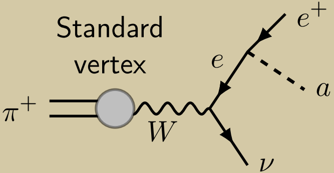

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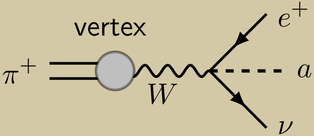

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Experimental Capabilities

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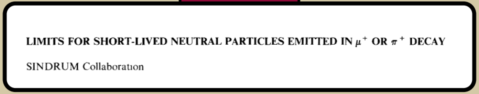
Past



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

SINDRUM Collaboration

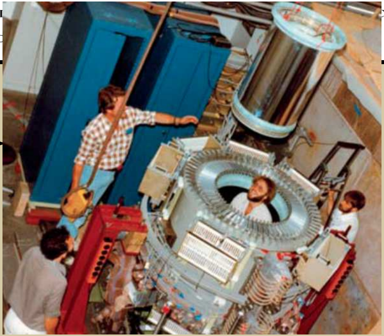
↳ Experiment in 80s at CERN

Experimental Capabilities

Past

LIMI **CAY**

SIND



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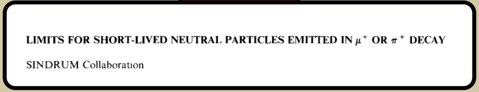

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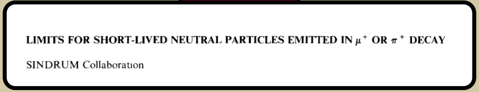

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Future

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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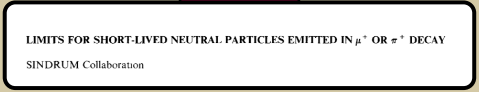

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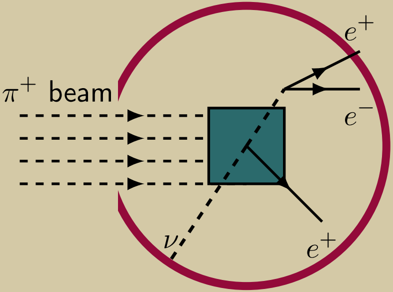

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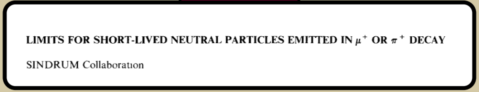

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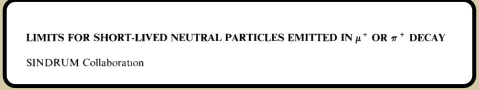

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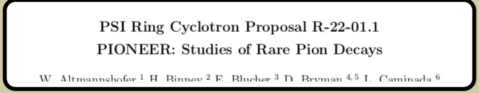

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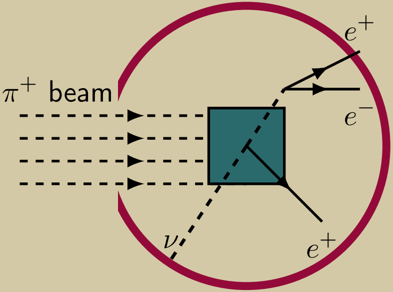

- Reach $\mathrm{Br}_{\pi^+\to e^+\nu a} \lesssim 10^{-11}$?

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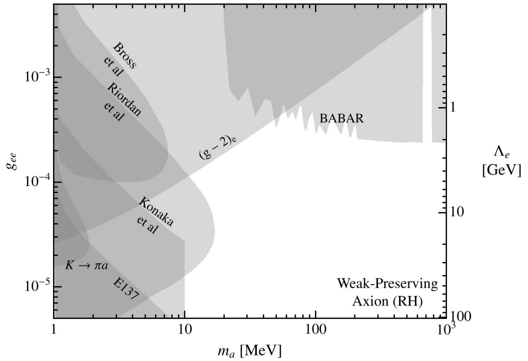

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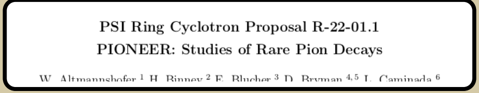

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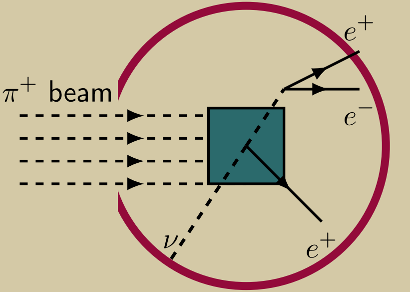

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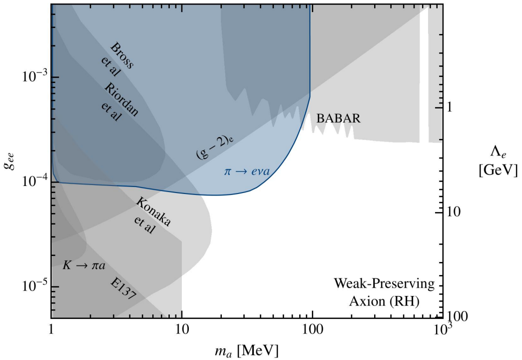

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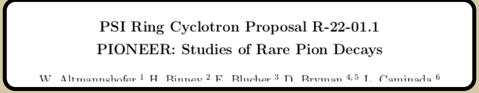

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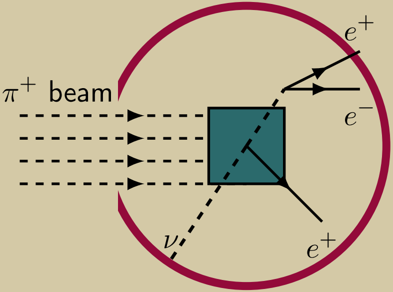

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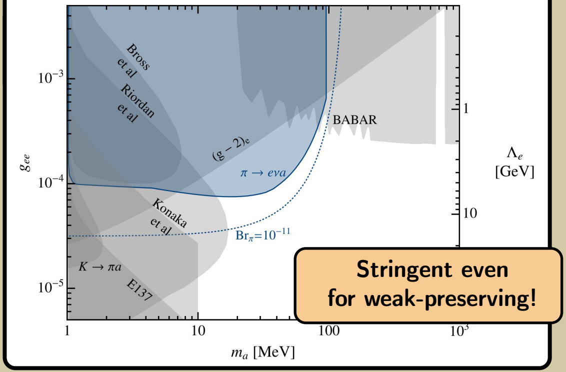

Stringent even for weak-preserving!

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Future

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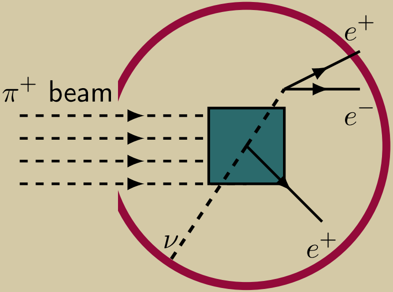

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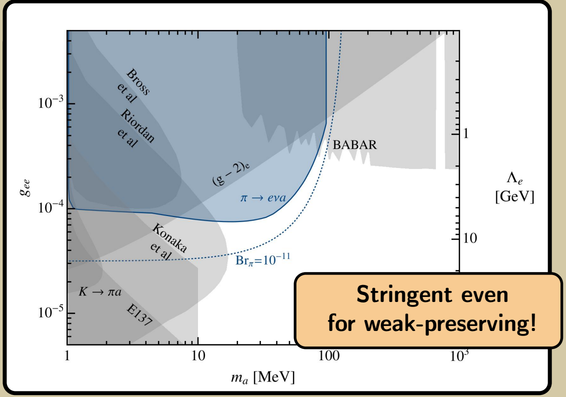

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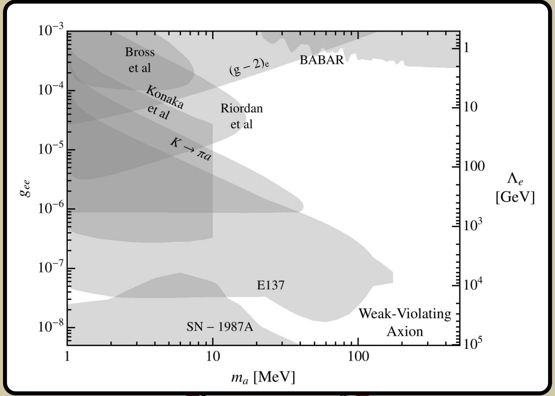

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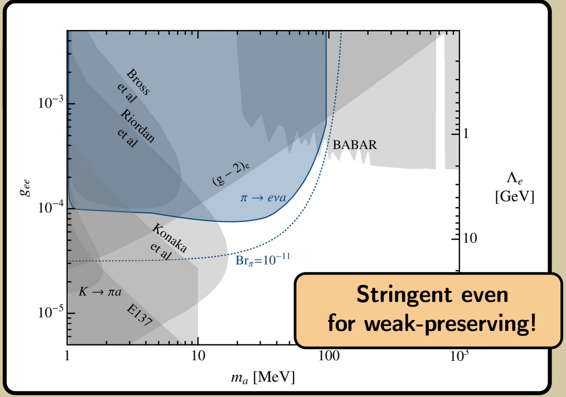

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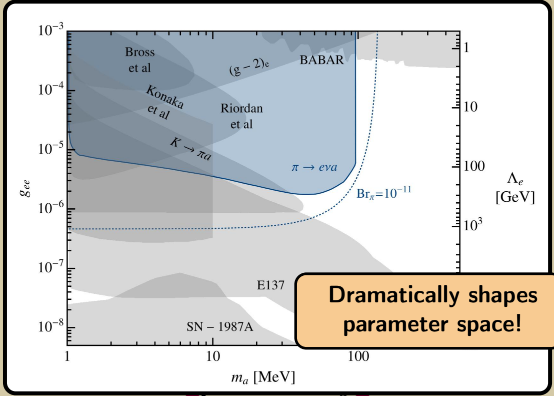


Dramatically shapes parameter space!

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

Other charged mesons

Win by $m_{\rm meson}^2/m_e^2$

Kaons

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

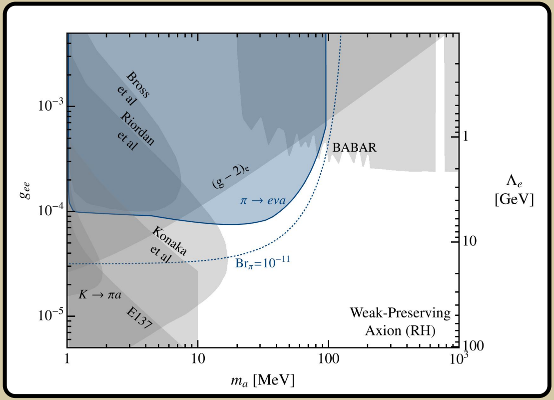
$$\mathrm{Br}_{K+\to e^+\nu a} \lesssim 3\times 10^{-8}$$

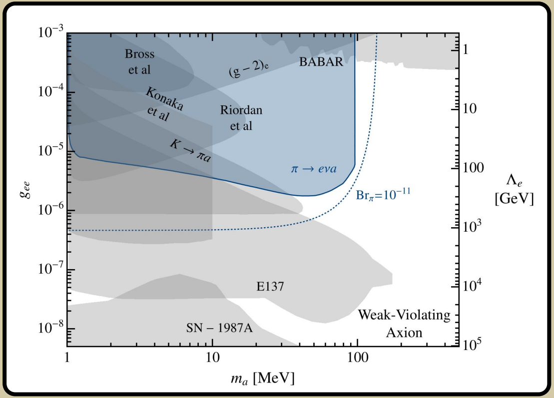
[**Exp 865** - '02]

- Improve with Kaon factories

Other charged mesons

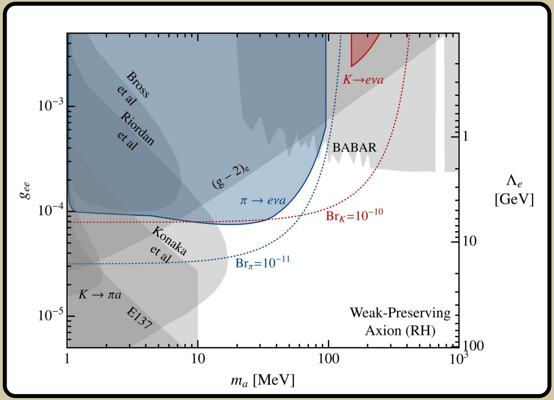
Win by m_{meson}^2/m_e^2

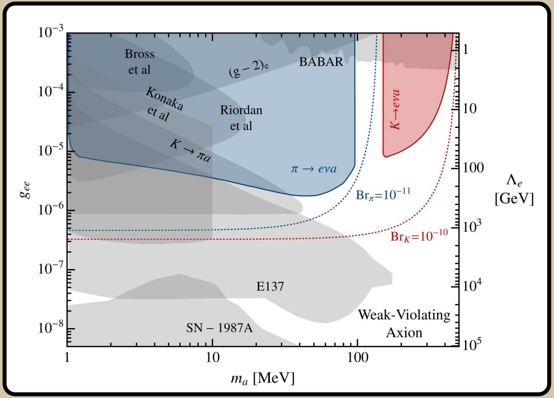




Other charged mesons

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





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[Exp 865 - '02]

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D/D_s meson

- Large $D^+ \to K^+ + X$ rate
- Suppresses branching ratio
- D_s wins by CKM factor
- Need to reach $\mathcal{O}(10^{-6})$

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[Exp 865 - '02]

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B/B_c meson

- Motivation for B_c physics?

W^+ boson decay

W^+ boson decay

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

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

Irrelevant for weak-preserving

W^+ boson decay

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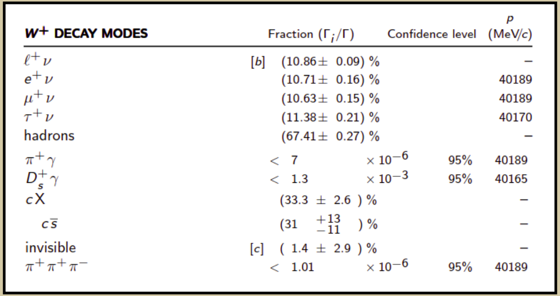
Irrelevant for weak-preserving

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

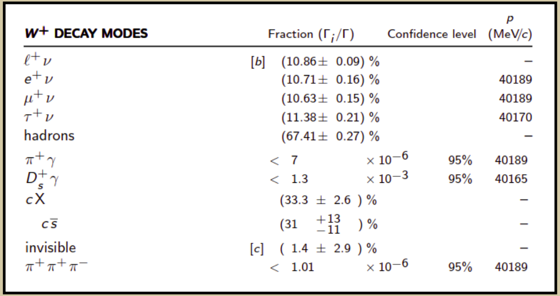
W^+ boson decay

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

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

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

↳ Contribute to total width,

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

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

↳ Dedicated search:

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

W^+ boson decay

W boson decay width
for weak-violatin

Irrelevant for
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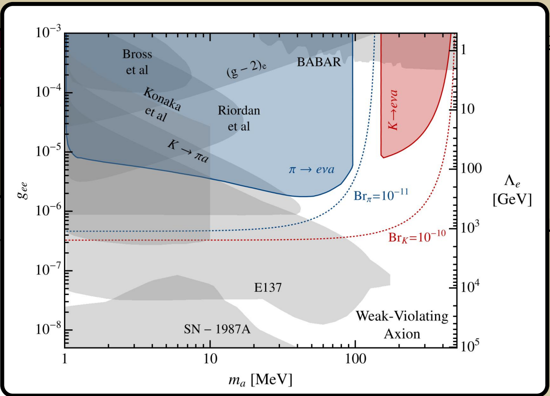

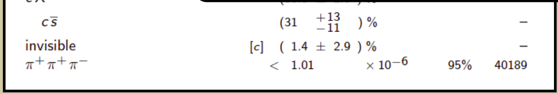

W^+ DECAY MODES

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

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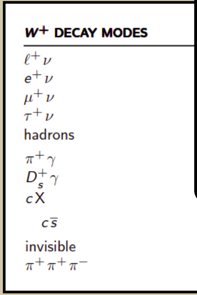
W^+ boson decay

W boson decay width for weak-violatin

Irrelevant for weak-preserving



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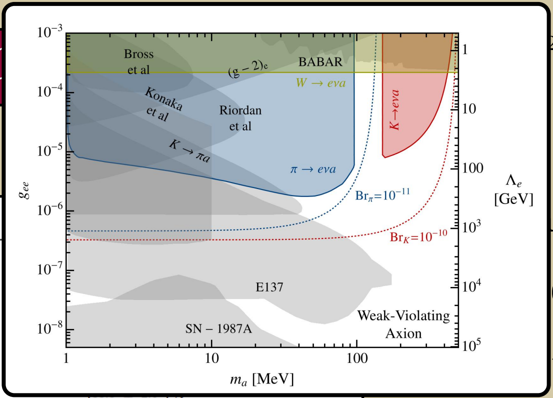

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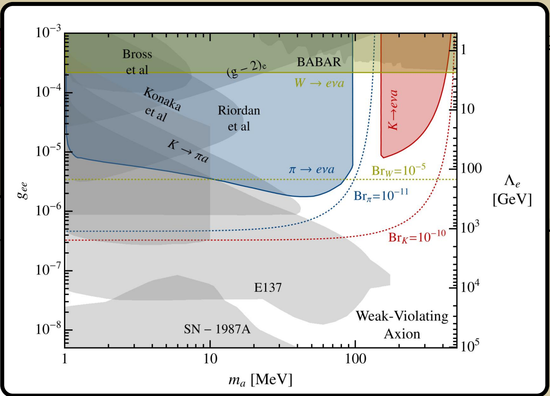

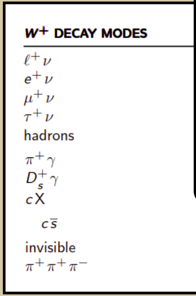

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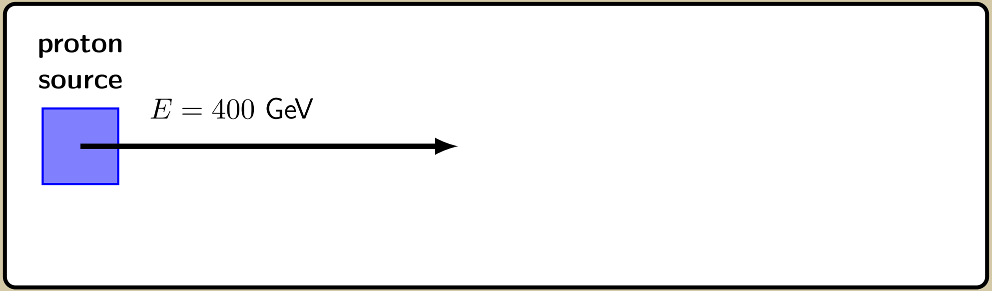
Proton beam dump experiments

Ex: CHARM experiment



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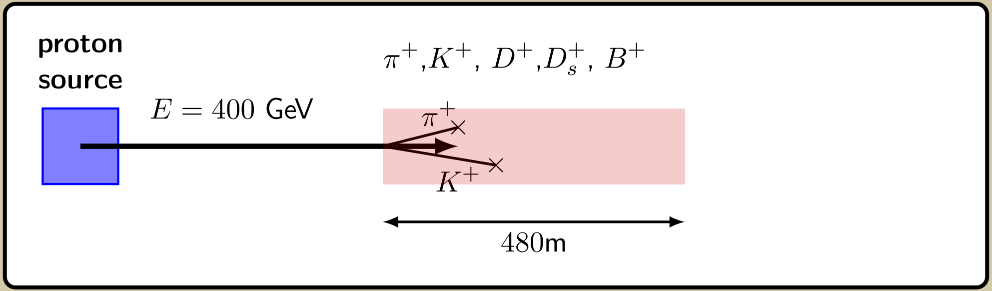

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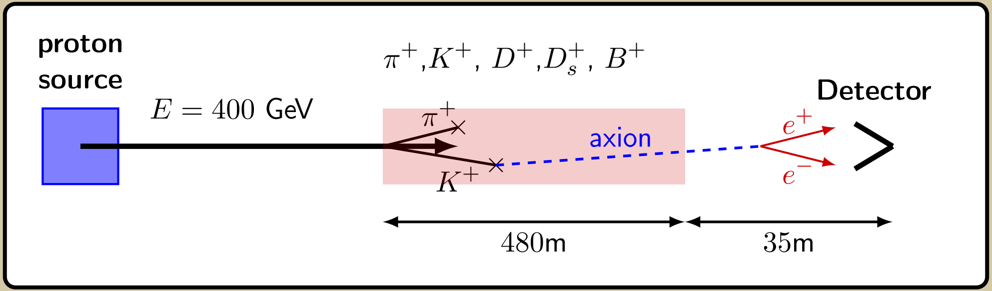

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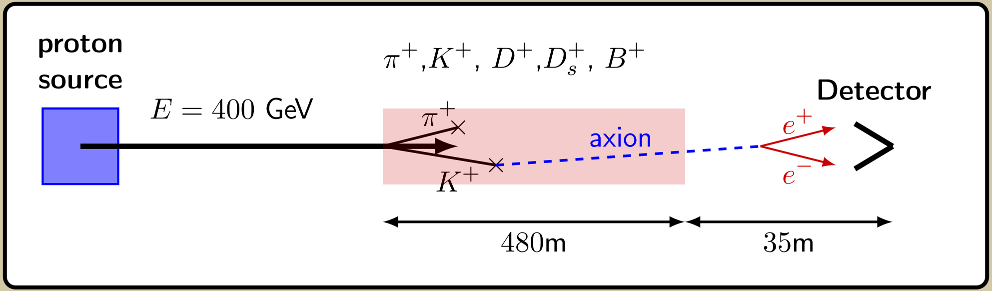

First use of D, D_s, B_c mesons

Observed zero events [CHARM - 1985]

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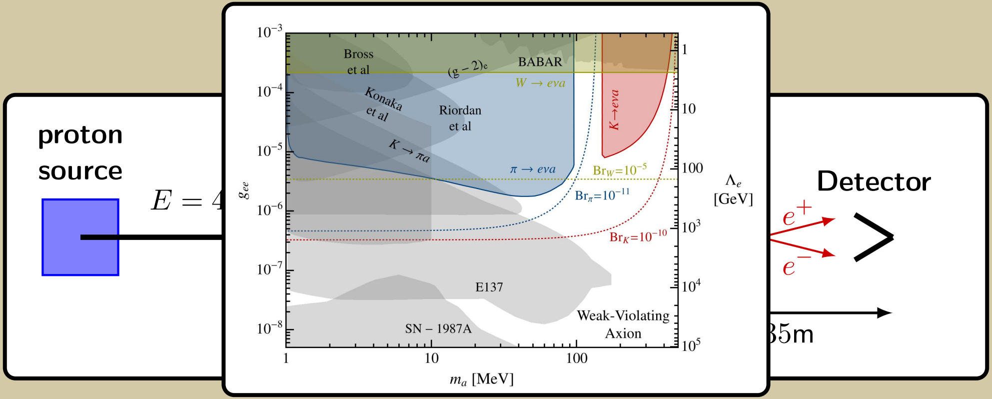

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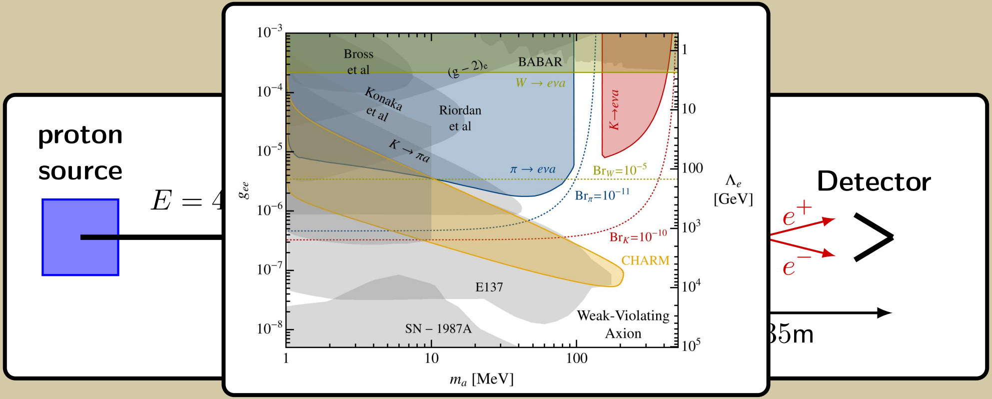

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Implications

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[Alves, Weiner - ’17] , [Alves - ’21]
revisited possibility of
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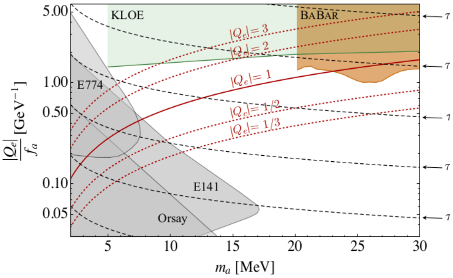

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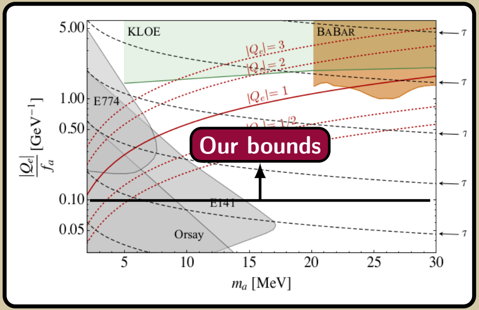

Our bounds

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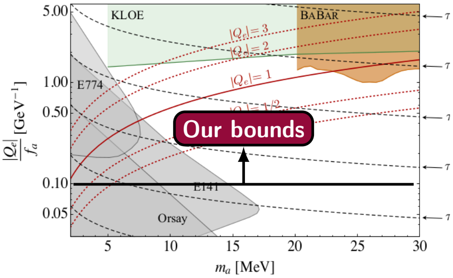

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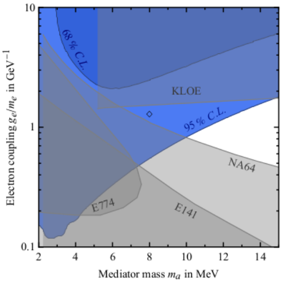
[Buttazzo et al - ’21] propose ALP mediate Xenon-1T excess



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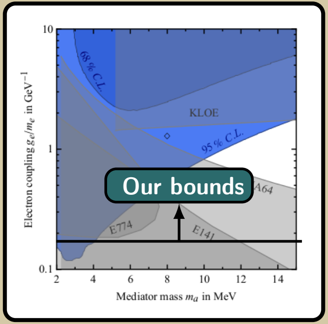

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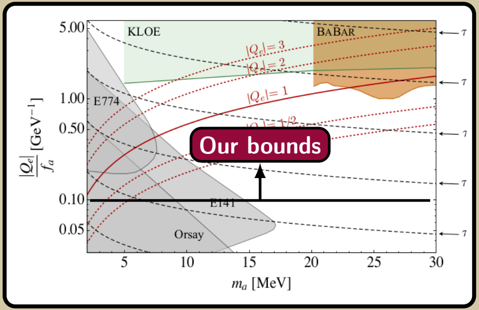

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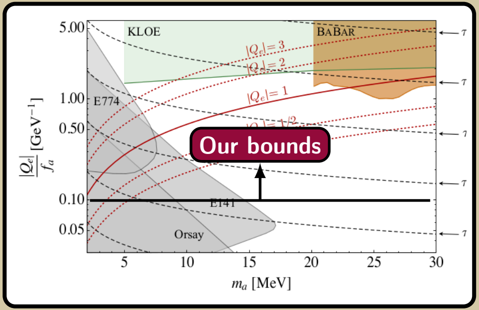

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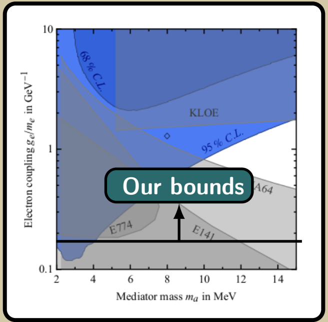

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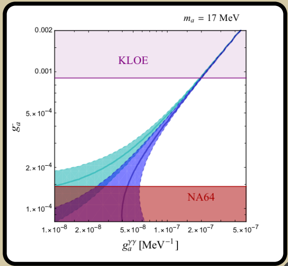

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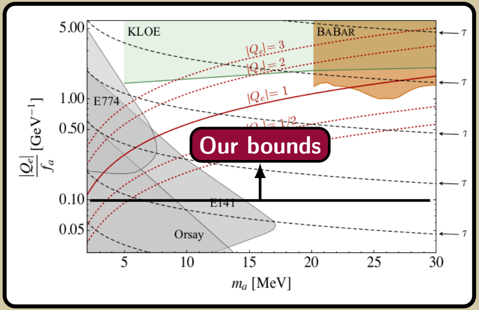

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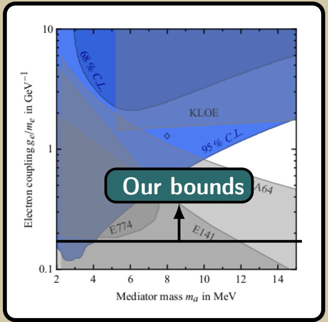

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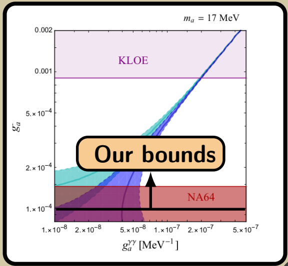

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Summary

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Need to distinguish

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Strong bounds in either case

Charged meson decays

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Final musings

Weak-violating ALPs drive new phenomenology

Every model has some weak-violation. Implications?