# Leptophilic ALPs with TWIST data in muon decay


Samadrita Mukherjee


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With Ankita Budhraja (Nikhef) and Sahana Narasimha (U Vienna)


CHEP, IISc, Bengaluru

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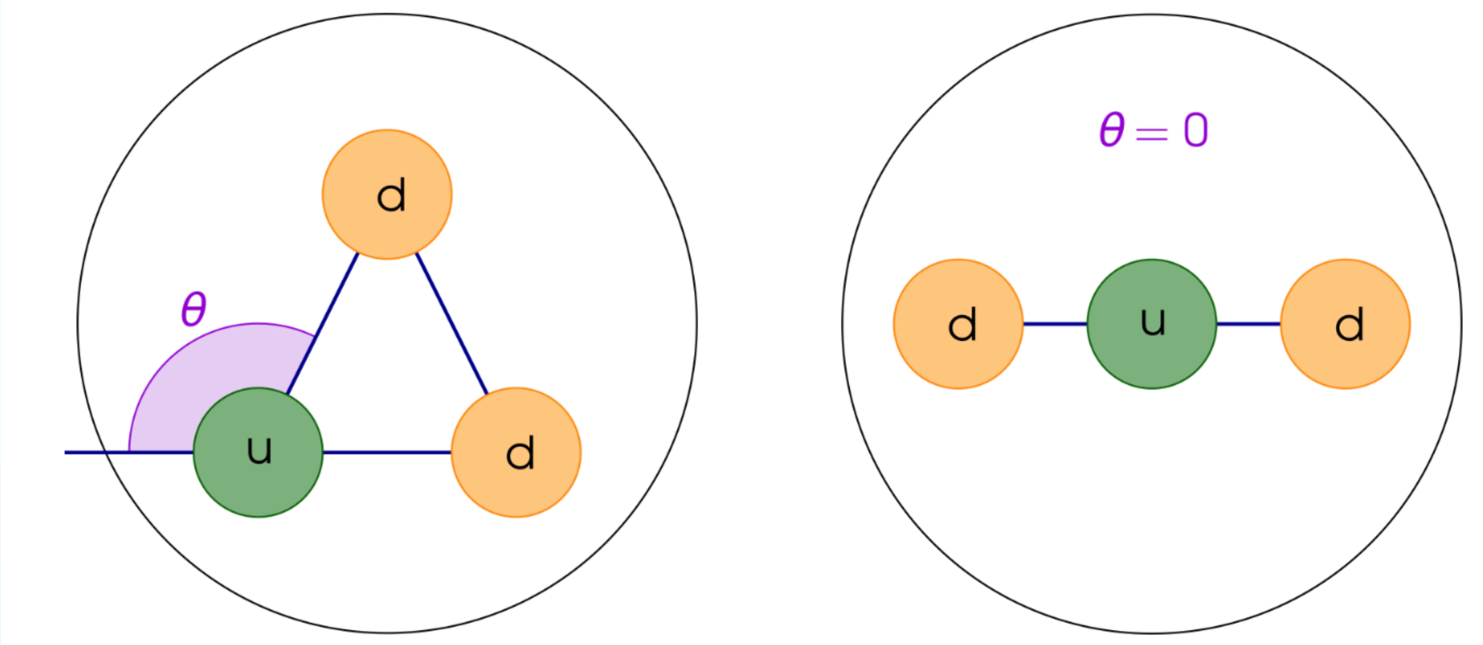
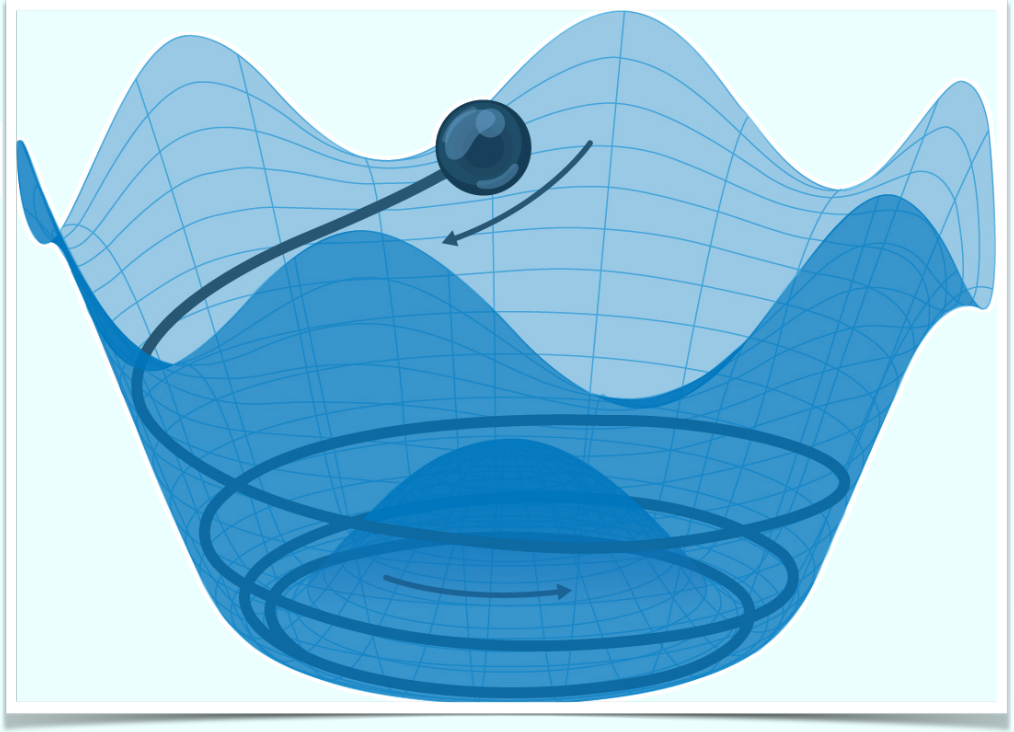
# Why Axion and What are ALPs

Theorized independently by Frank Wilczek and Steven Weinberg as the Goldstone boson of Peccei–Quinn theory, to solve the strong CP problem in QCD.



- ALPs are a generic class of light new BSM particles

- Light neutral scalars or pseudo scalars that couples weakly to normal matter and radiation.
- Such bosons may arise from the spontaneous breaking of a global U(1) symmetry, resulting in a massless Nambu-Goldstone boson.
- If there is a small explicit symmetry breaking, either already in the Lagrangian or due to quantum effects such as anomalies, the boson acquires a mass and is called a pseudo-NG boson.

# ALPs coupled to...

Models of QCD axions typically predict specific coupling patterns and relate the coupling strength and axion mass

- **Model-independent approach**

- Couplings can vary independently
- No relation between couplings and mass
- Consider generic effective interactions

$$\boxed{\frac{C_{a\gamma\gamma}}{\Lambda} a F_{\mu\nu} \tilde{F}_{\mu\nu}}$$

With EW gauge bosons

$$\boxed{-\frac{i}{2\Lambda} g_d a \bar{N} \sigma_{\mu\nu} \gamma_5 N F_{\mu\nu}}$$

To nucleon EDM

- **In general ALPs can couple to**

- Electroweak gauge bosons
- SM fermions
- Gluons
- SM Higgs bosons
- All of the above

$$\boxed{-\frac{g_{aee}}{\Lambda} \partial_\mu a \bar{f} \gamma_\mu \gamma_5 f}$$

To axial electron moment

Brivio et al., arXiv:1701.05379

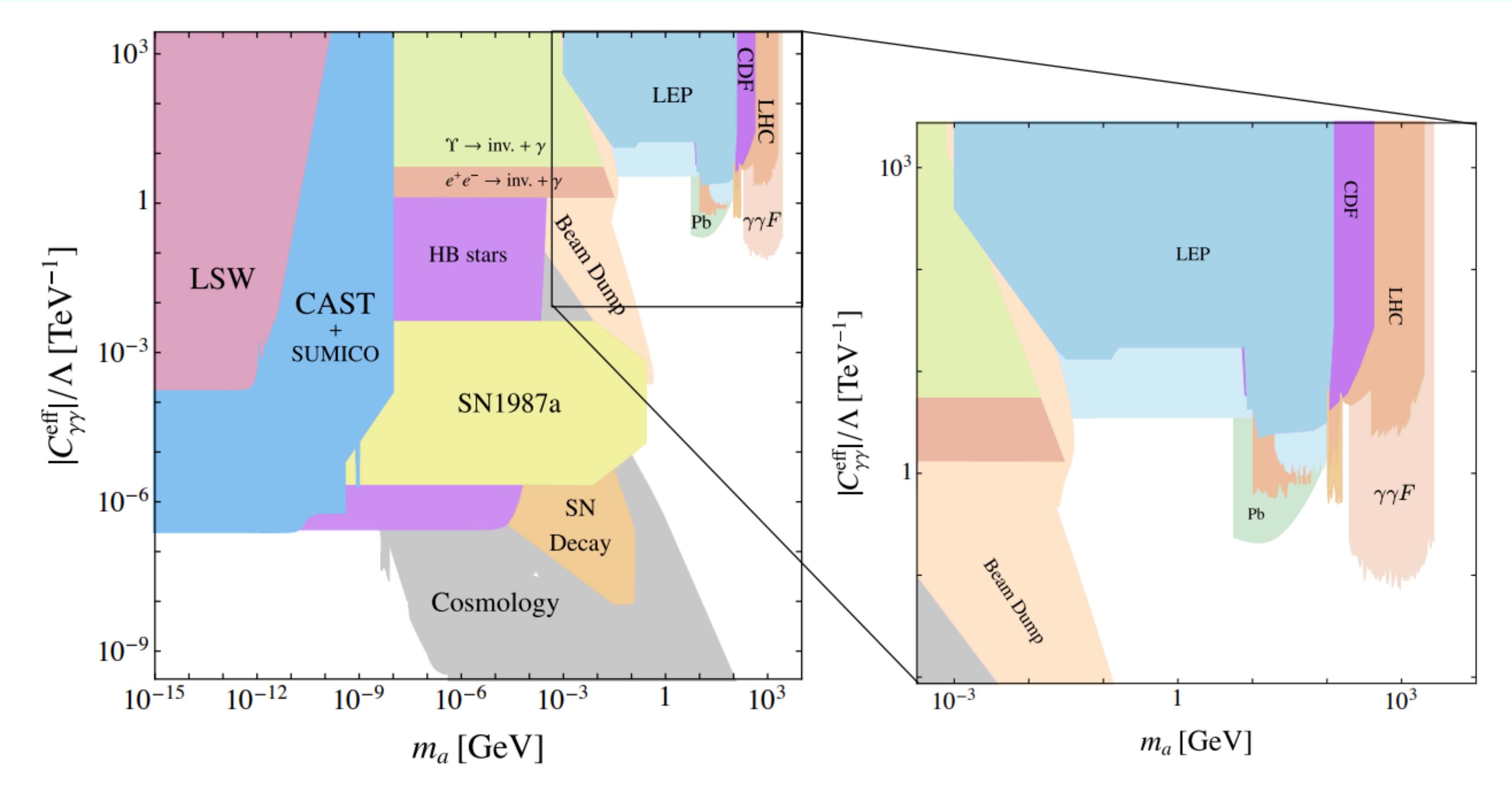
Izaguirre et al., arXiv:1611.09355

Bauer et al., arXiv:1708.00443

# Types of axion experiments typically fall in many categories

ALP masses below the MeV scale

- Very strong astrophysical constraints
- Couplings to photons must be tiny
- ALPs nearly stable – could be dark matter !




Ref: Baur et al. 1808.10323

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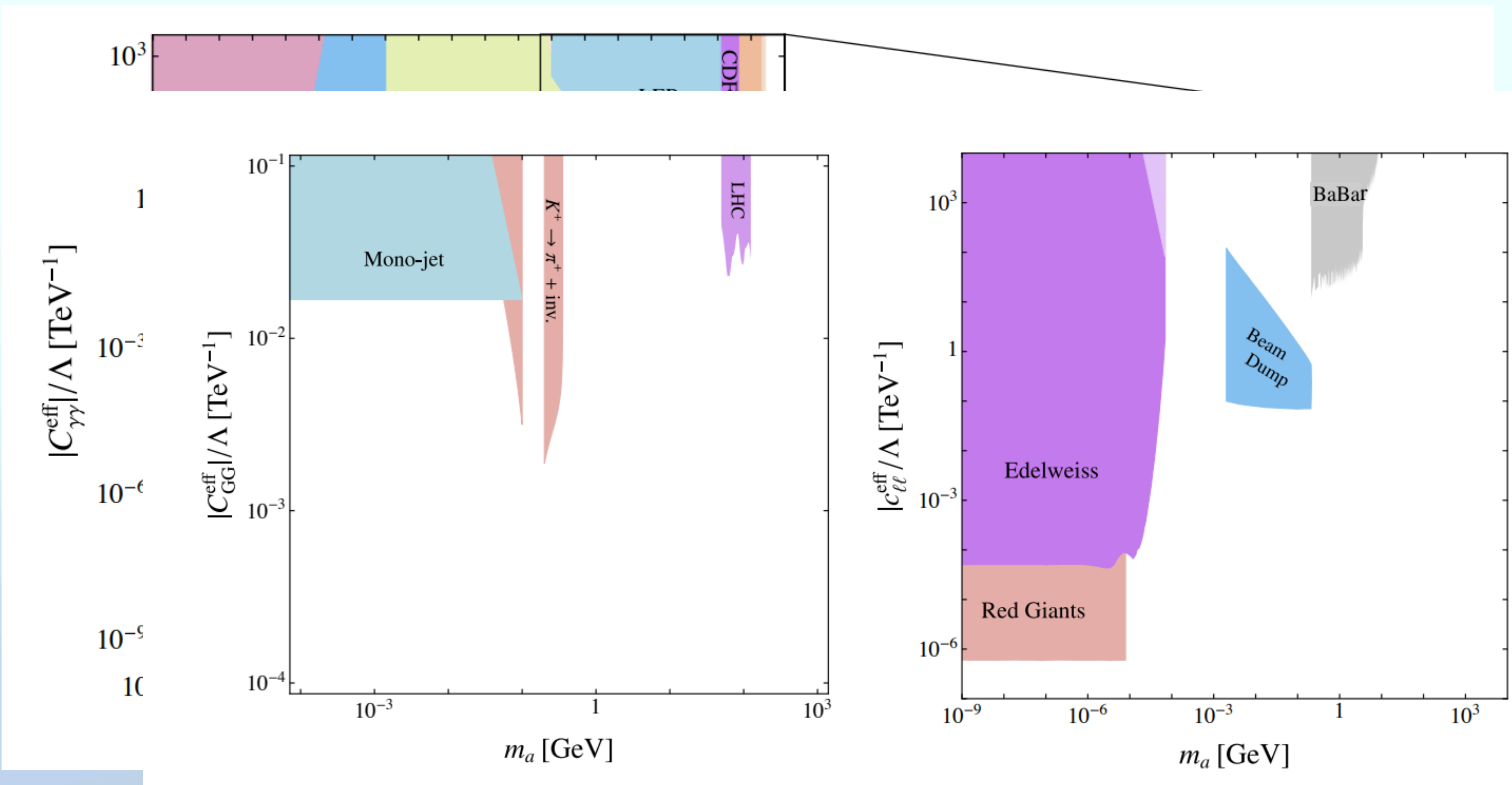


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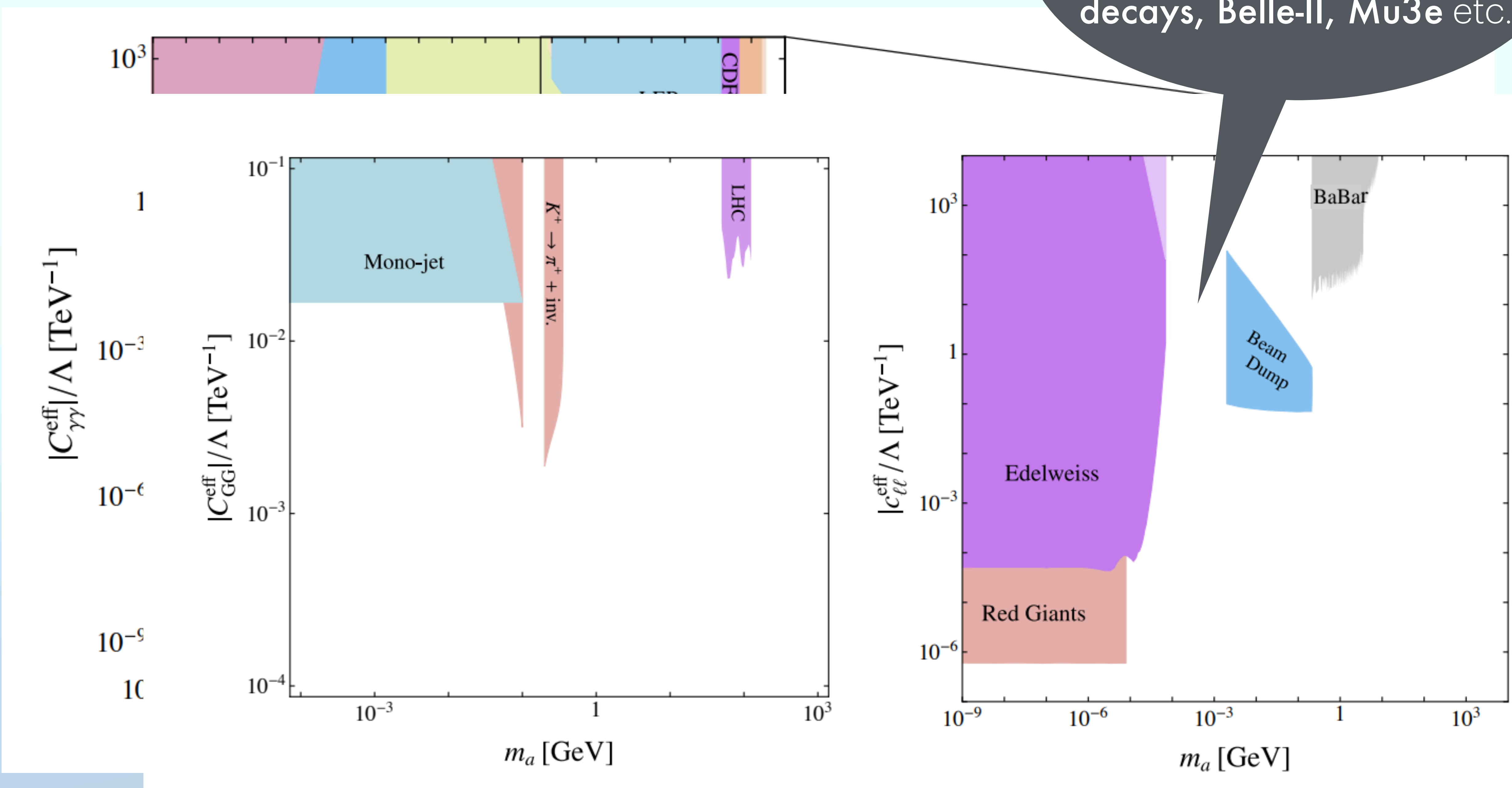
In the Axion-lepton coupling plane, there are other results from Meson decays, Belle-II, Mu3e etc.



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# This Study: ALPs primarily connected with leptons.

To investigating the production of light ALPs alongside electrons and neutrinos in the Standard Model muon decay process:

$$\mu^{\pm} \to e^{\pm}\nu_{\mu}\bar{\nu}_{e}\phi$$

The cleanest production channel due to:

- the definite measurement of muon lifetime
- the absence of hadrons in the decay process
- reduced uncertainties associated with hadronic in-states.

$$\boxed{\mathscr{L} \supset G_F \left(\bar{\mu}\gamma^{\rho} P_L \nu_{\mu}\right)\left(\bar{\nu}_e \gamma_{\rho} P_L e\right)}$$

$$\boxed{\mathscr{L}_{BSM} \supset \frac{g_{\phi l}}{m_l} G_F\, \phi \left(\bar{\mu}\gamma^{\rho} P_L \nu_{\mu}\right)\left(\bar{\nu}_e \gamma_{\rho} P_L e\right)}$$

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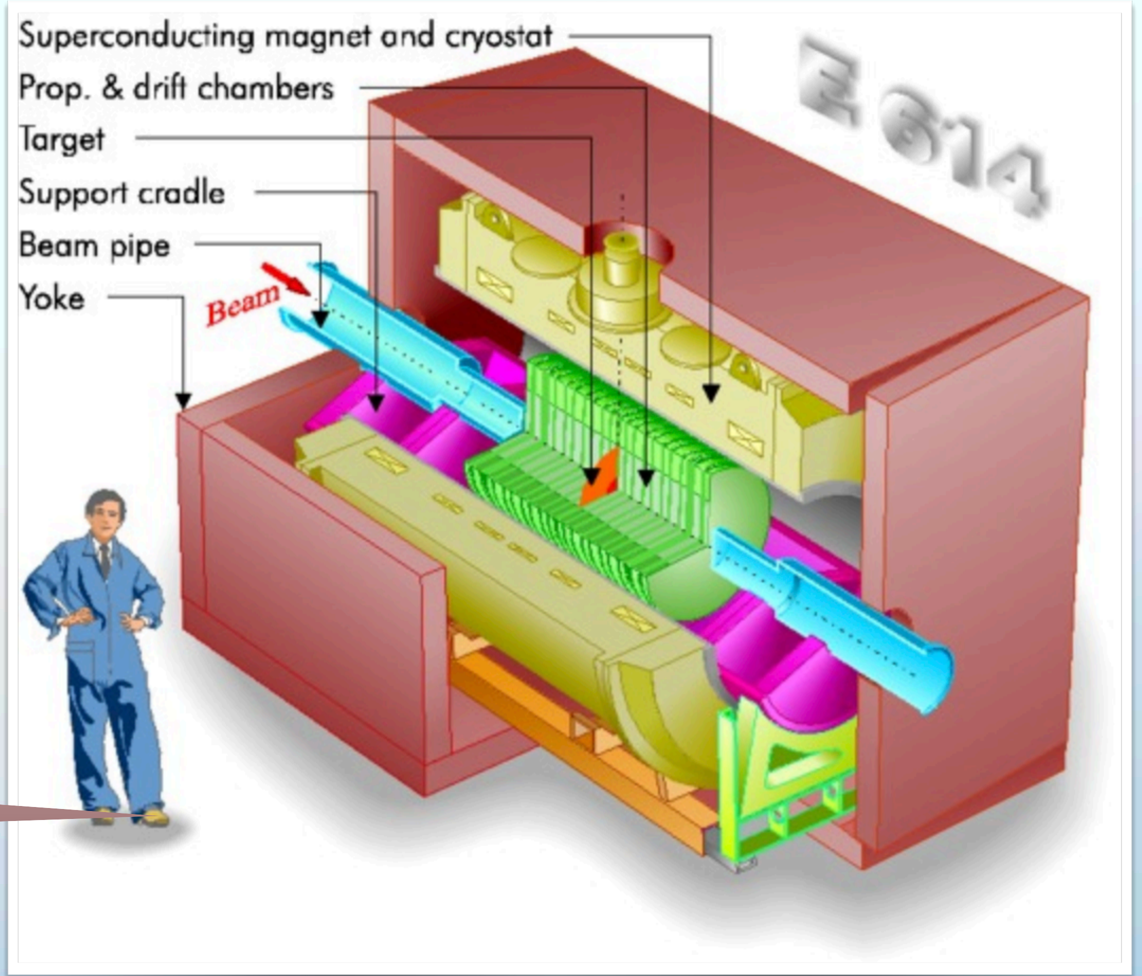
Where do we look for it ?

# The TRIUMF Weak Interaction Symmetry Test

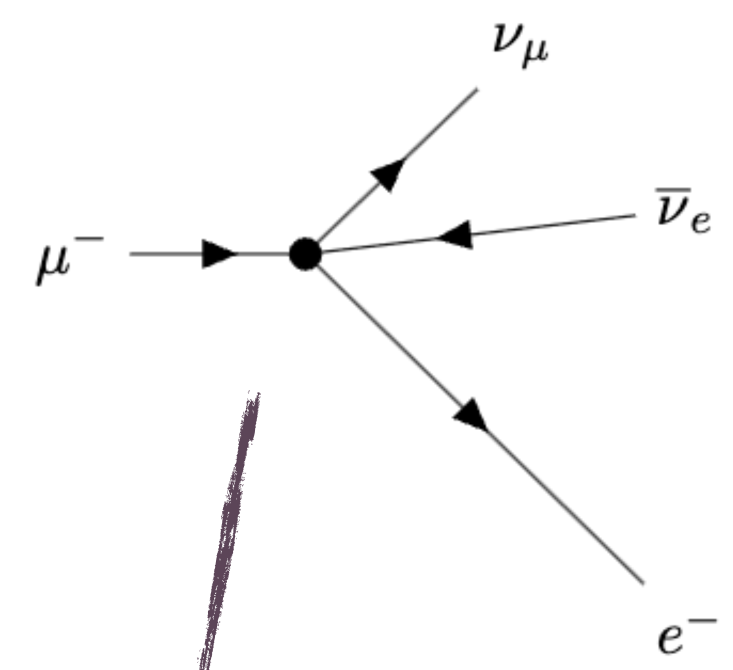
- TWIST measures the decay distributions of polarized muons.
- Distributions which are differential in energy and angle will be determined to a precision of parts in 10,000, allowing a determination of the parameters of the standard model which characterize the muon decay.

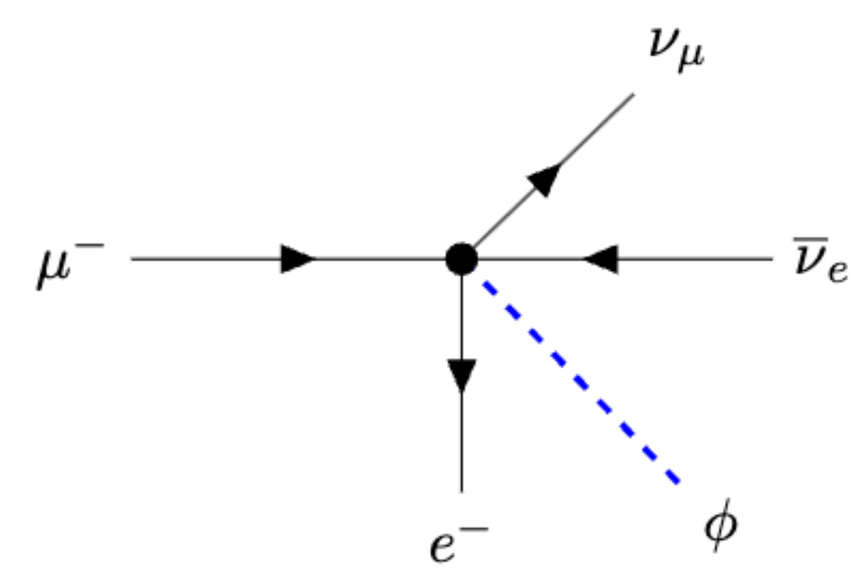
The Collaboration tested V-A theories with high-precision measurements of the decay of the muon.

Might be the ideal place to look for BSM Physics in Muon Decay



# The 3-body and 4-body Decay



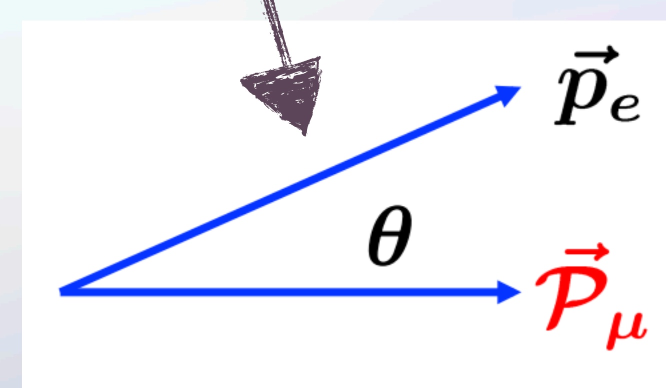

$$\frac{d^2\Gamma_3(\mu^\pm \to e^\pm \nu\bar{\nu})}{dE_e\, d\left(\cos\theta_e\right)} = \frac{G_F^2 m_\mu^2}{24\pi^3}|\vec{k}_e|\left\{3E_e - \frac{4E_e^2}{m_\mu} + \frac{3\,m_e^2}{m_\mu^2}E_e - \frac{2\,m_e^2}{m_\mu} \pm |\vec{k}_e|P_\mu\cos\theta\left(1 - \frac{4E_e}{m_\mu} - \frac{3\,m_e^2}{m_\mu^2}\right)\right\}$$

This can be re-written in terms of Michel parameters

## Muon decay parameters

$$\rho, \eta, P_\mu\xi, \delta$$

$$\boxed{\Gamma_{3b} = \frac{G_F^2\, m_\mu^5}{192\,\pi^3}}$$

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C. Bouchiat and L. Michel, Phys. Rev. 106, 170 (1957).
T. Kinoshita and A. Sirlin, Phys. Rev. 107, 593 (1957).

# The 4-body Decay

$$\frac{d^2\Gamma_4(\mu^\pm \to e^\pm \nu\bar{\nu}\phi)}{dE_e d\cos\theta_e} = \frac{G_F^2 g_{\phi l}^2}{192\pi^5 m_l^2}|\vec{k}_e| \times \Big\{ \Big(6m_\mu^2 E_e + 6m_e^2 E_e + 2m_\phi^2 E_e - 8m_\mu E_e^2 - 4m_e^2 m_\mu \mp 2m_\mu^2 |\vec{k}_e| P_\mu \cos\theta_e$$

$$\mp 6m_e^2|\vec{k}_e|P_\mu\cos\theta_e \mp 2m_\phi^2|\vec{k}_e|P_\mu\cos\theta_e \pm 8m_\mu E_e|\vec{k}_e|P_\mu\cos\theta_e\Big)I_1 + \Big(4m_e^2 + 8E_e^2 - 12m_\mu E_e$$

$$\pm 4m_\mu|\vec{k}_e|P_\mu\cos\theta_e \mp 8E_e|\vec{k}_e|P_\mu\cos\theta_e\Big)I_2 + 4E_e I_3 \pm \frac{4}{3}|\vec{k}_e|P_\mu\cos\theta_e I_4\Big\}$$

$$I_1 = \int\sqrt{E_\phi^2 - m_\phi^2}\,dE_\phi\,, \qquad I_2 = \int E_\phi\sqrt{E_\phi^2 - m_\phi^2}\,dE_\phi\,, \qquad I_3 = \int E_\phi^2\sqrt{E_\phi^2 - m_\phi^2}\,dE_\phi\,, \qquad I_4 = \int\left(E_\phi^2 - m_\phi^2\right)^{\frac{3}{2}}\,dE_\phi\,.$$

$$\boxed{m_\phi \le E_\phi \le \frac{m_\mu}{2} + \frac{m_e^2}{2m_\mu} + \frac{m_\phi^2}{2m_\mu} - E_e}$$

Lower Limit and upper limit on $E_\phi$

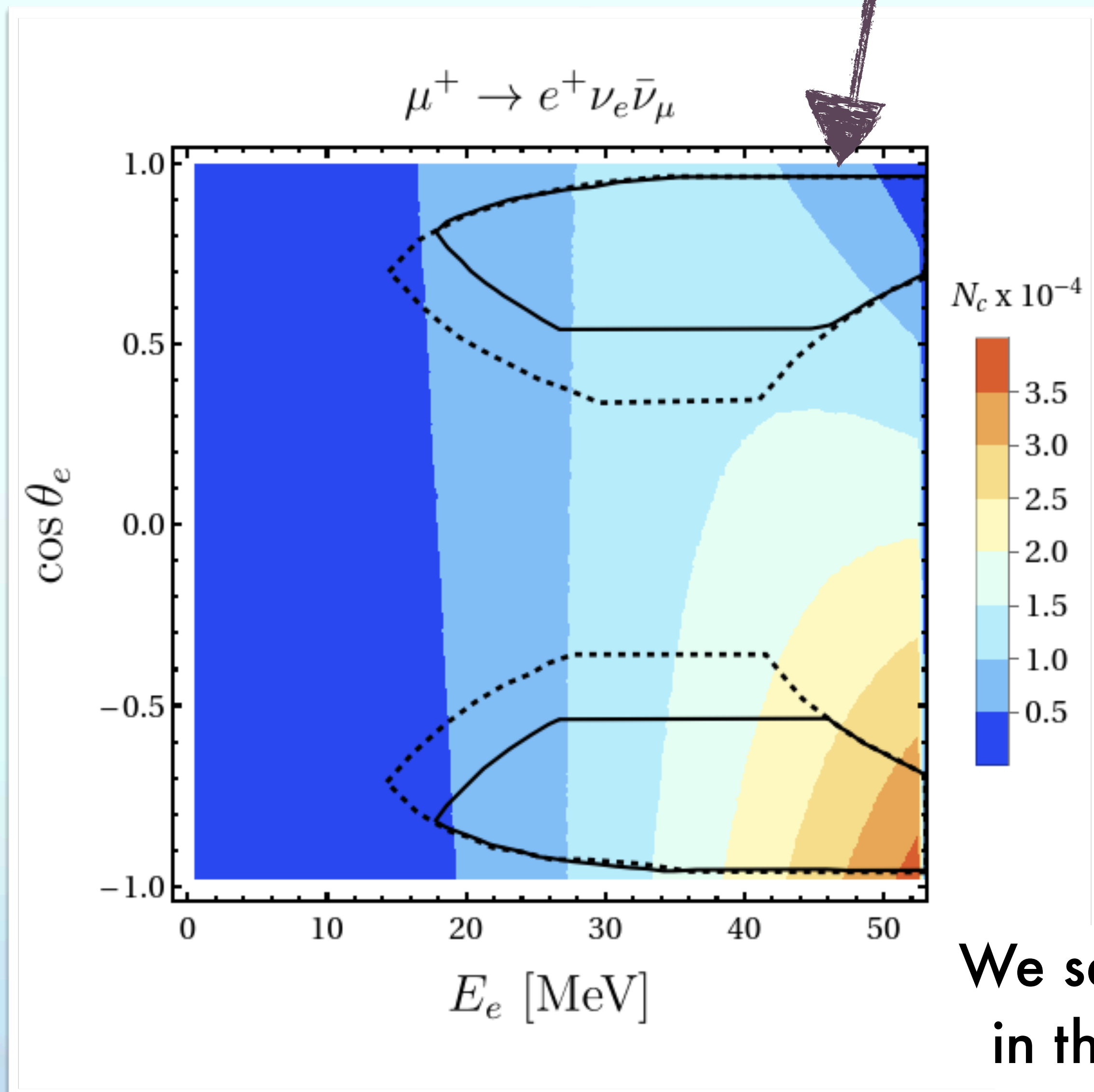
Total decay width, neglecting $m_\phi$

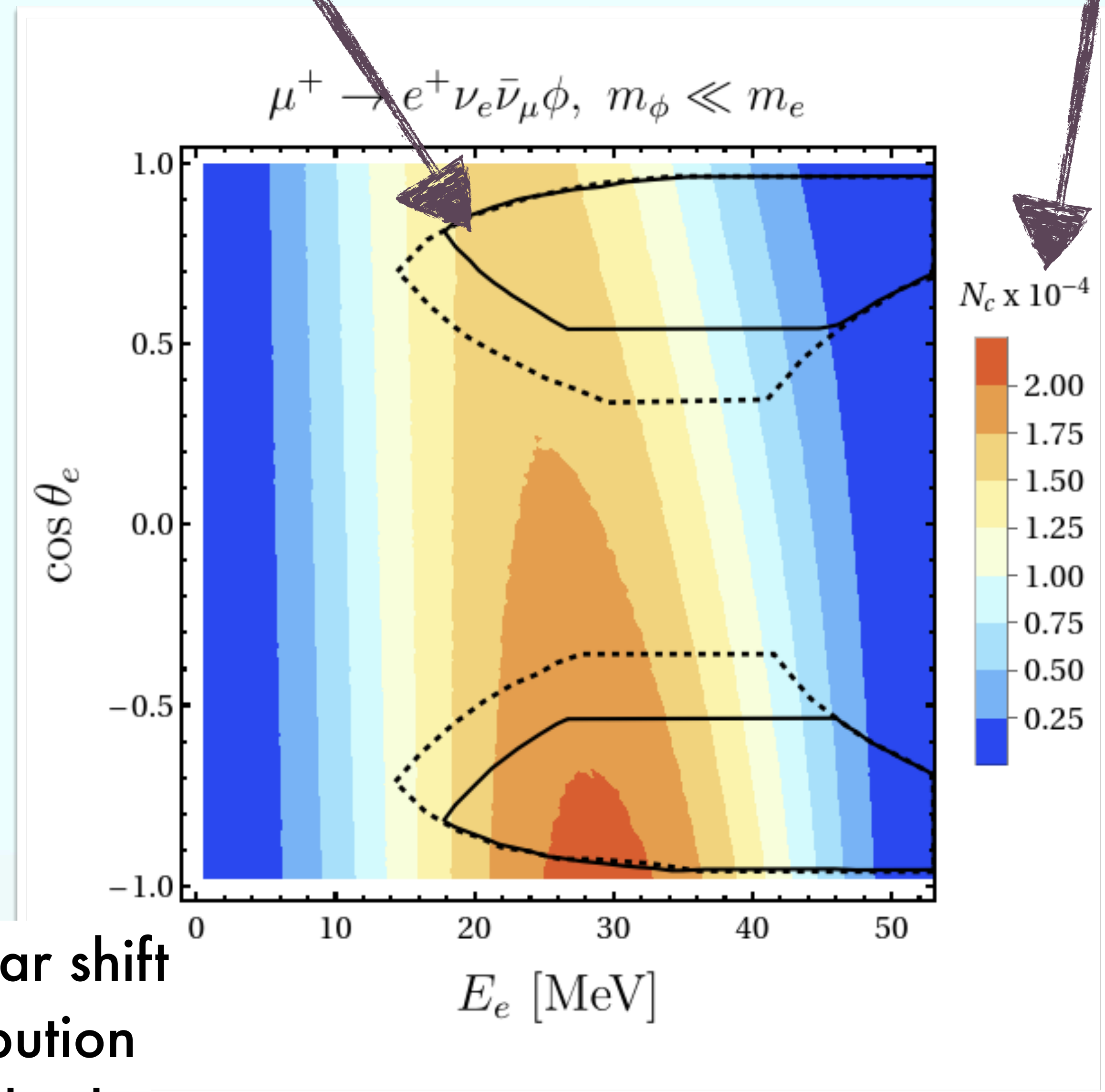
$$\boxed{\Gamma_{4b} = \frac{G_F^2\, m_\mu^5}{192\,\pi^3}\left(\frac{17\,m_\mu^2}{6720\,\pi^2} - \frac{m_e^2}{96\pi^2}\right)\frac{g_{\phi l}^2}{m_l^2}}$$

# Differential Distribution of Muon Decay

Fiducial regions used in the experiment.

The number of events in each bin normalized to the total number of events generated

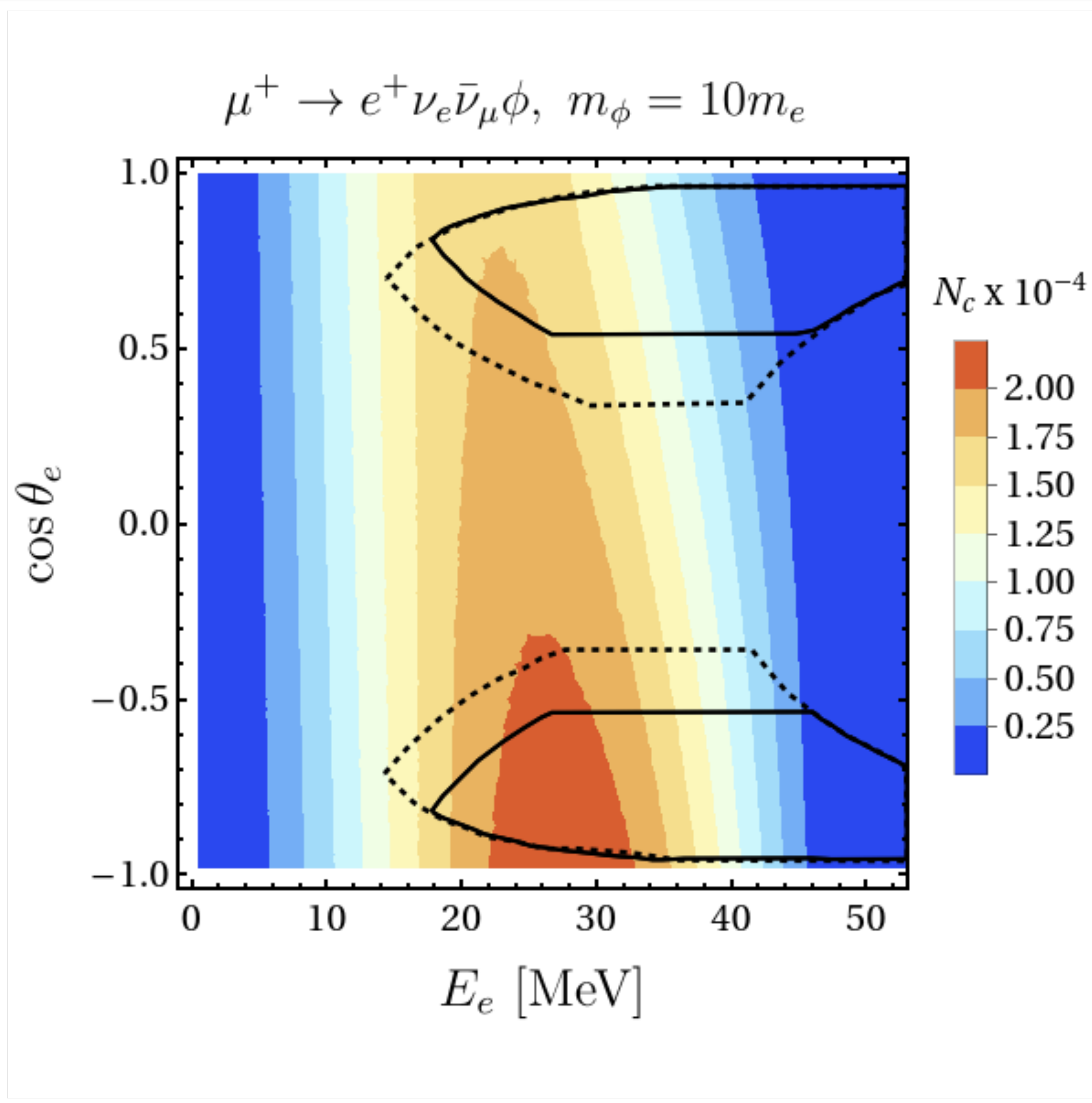


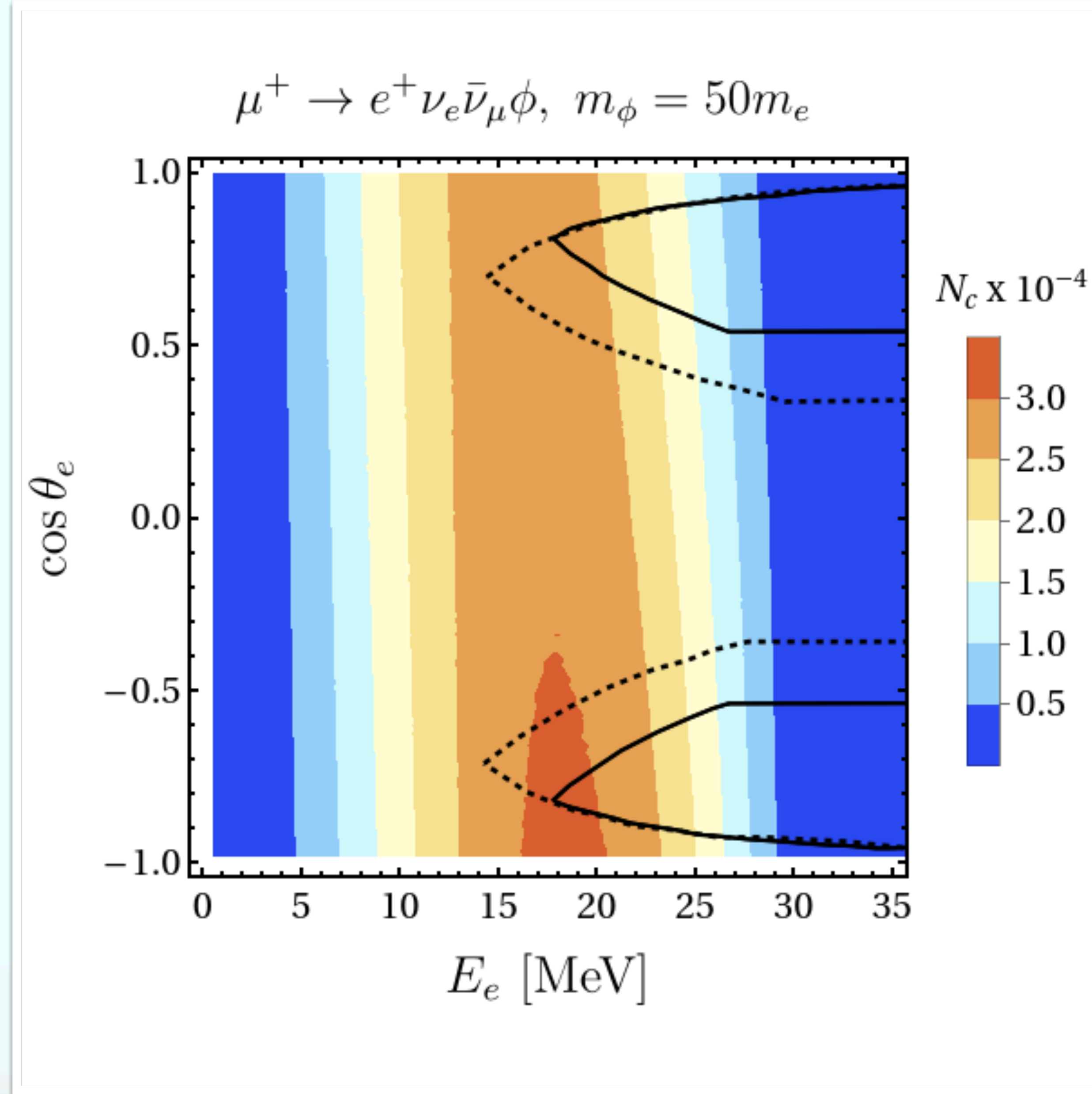




We see a clear shift in the distribution for the four-body decay

**The scale of new physics can be obtained**

# With increasing ALP mass




- The allowed energy available to the outgoing electron (positron) is reduced.

- Note that with the same set of fiducial cuts, a lower number of events will survive in the allowed region for the case of the heavier ALPs.

# Simulation details for the differential analysis

To obtain the best-fit value of NP coefficient

$$\chi^2(g_{\phi l}, \alpha) = N_{obs}^{fid} \sum_{x,y}^{n} \frac{[F(g_{\phi l}, \alpha; x, y) - \mathcal{G}(x,y)]^2}{\mathcal{G}^2(x,y)}$$

$$F(g_{\phi l}, \alpha; x, y) = (1-\alpha) f_{3b}(x,y) + \alpha f_{4b}(g_{\phi l}, \alpha; x, y)$$

normalized binned data of the $e^-(e^+)$ generated via the differential decay distribution.

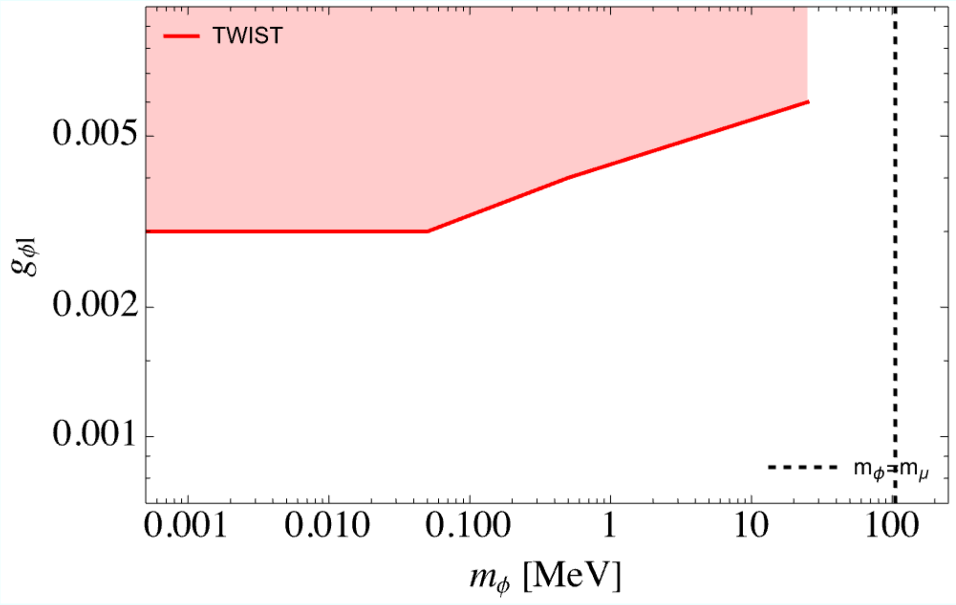
- With this construction, we ensure that all the radiative corrections and detector effects are properly cancelled inside the function $\mathcal{G}(x,y)$, as the function $F(g_{\phi l}, \alpha; x, y)$ contains only the leading order effects.

$$\mathcal{G}(x,y) = \frac{f_{3b}(x,y)\,.\,d_T(x,y)}{f_T(x,y)}$$

data and fit values with the same binning along x and y direction as obtained from the experimental side.

# The NP Coupling

| ALP Mass [MeV] | Events in the fiducial area ($N_{4b}^{fid}$) | $g_{\phi l}$ |
|---|---|---|
| $m_e/100$ | $238 \times 10^6$ | $3 \times 10^{-3}$ |
| $m_e$ | $238 \times 10^6$ | $3 \times 10^{-3}$ |
| $10m_e$ | $226 \times 10^6$ | $4 \times 10^{-3}$ |
| $50m_e$ | $94 \times 10^6$ | $6 \times 10^{-3}$ |




Leptonic decays of various mesons, e.g. $\pi^{\pm} \to e^{\pm}\nu\phi$, $K^{\pm} \to e^{\pm}\nu\phi$.

LFV coupling among the electron, muon and ALP : $\mu \to e\phi$.

Other relevant constraints

It is required to point out that these may not be a one-to-one comparison to the particular operator discussed here for two reasons.

- In meson decays, it is not possible to disentangle the ALP-lepton interaction vertex from the ALP-quark interactions. Second, these set-ups utilizes ALP decays to visible states and not long-lived enough — these should not necessarily be treated on the same footing.

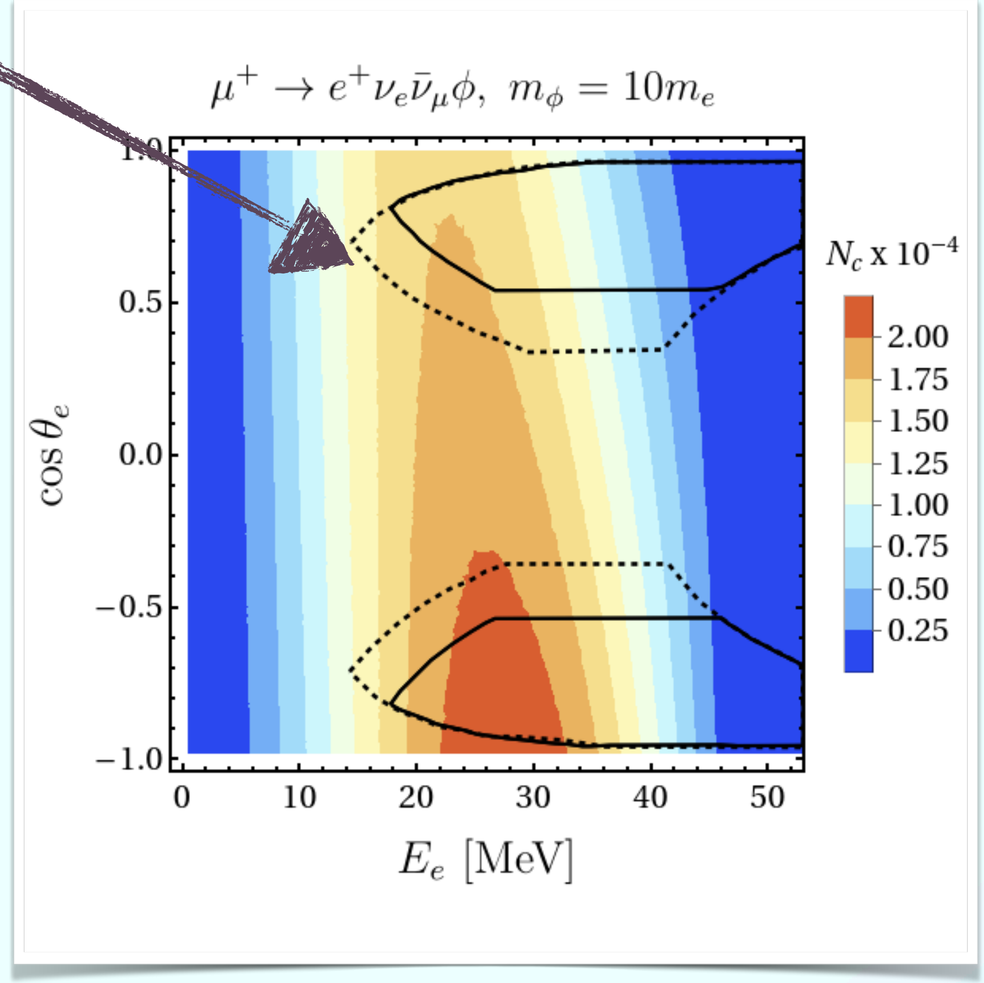
- The Mu3e experiment is also capable of detecting or constraining light new resonances producing prompt electron-positron final states.

# We propose a new fiducial region

- The constraint gets weaker with increasing ALP masses.

- The maxima of the energy distribution of the emitted electron shifts to much lower values → the number of events surviving inside the experimentally accessible region reduces.
- Modify the fiducial cuts in our simulations with the goal of enhancing the NP contribution.

- Additionally, we would like to ensure that this region is realistically achievable in experiments.




| ALP Mass [MeV] | TWIST Cuts | | Proposed Cuts | |
|---|---|---|---|---|
| | $N_{3b}^{fid}/N_{tot}$ | $N_{4b}^{fid}/N_{tot}$ | $N_{3b}^{fid}/N_{tot}$ | $N_{4b}^{fid}/N_{tot}$ |
| $m_e/100$ | - | 0.279 | - | 0.432 |
| $10m_e$ | 0.342 | 0.265 | 0.439 | 0.420 |
| $50m_e$ | - | 0.110 | - | 0.223 |

# Summary and Road Ahead

- ALPs produced in association with electrons and neutrinos within the muon decay.

- The dataset furnished by TWIST experiment is used to derive constraints on ALP-lepton couplings.

- The set-up we consider cleanly constrains only the ALP-lepton coupling in contrast to meson decay processes - a complementary search strategy.

- Even by extending the fiducial cuts within the TWIST set-up very minimally the experimental sensitivity towards such a NP can be enhanced.

- The forthcoming experimental endeavors involving muon beams, for e. g., MEG-II, Mu3e, we expect that reaching at least a count of $\mathcal{O}(10^{12})$ muons in a beam would be necessary to have a non-zero probability of the muon to decay to such a four-body final state.

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Thank You !

# Back-up Slides

# The full functional dependence of 4-body partial decay width

$$\mathcal{F} = \frac{1}{6720}\Bigg[840\, m_\phi^2 \left(\log(2m_\phi) - \log\left(\frac{m_\phi^2}{m_\mu} + 2m_\phi + f(m_\mu, m_\phi)\right)\right)\mathcal{I}_1(m_\mu, m_e, m_\phi) + \frac{840\, m_\phi^2}{m_\mu^3}$$
$$\log\left(m_\phi^2 + 2m_\mu m_\phi + m_\mu f(m_\mu, m_\phi)\right)\mathcal{I}_2(m_\mu, m_e, m_\phi) + \frac{m_\phi^2}{m_\mu^6} g(m_\mu, m_\phi)\mathcal{I}_3(m_\mu, m_e, m_\phi)$$
$$- \frac{840\, m_\phi^2}{m_\mu^3}\log(2m_\mu^2)\mathcal{I}_2(m_\mu, m_e, m_\phi) + \frac{g(m_\mu, m_\phi)}{m_\mu^6}\mathcal{I}_4(m_\mu, m_e, m_\phi)\Bigg],$$

$$f(m_\mu, m_\phi) = \sqrt{\frac{m_\phi^3(4m_\mu + m_\phi)}{m_\mu^2}} \text{ and } g(m_\mu, m_\phi) = \frac{(m_\mu^2 - m_\phi^2)}{m_\mu}$$

$$\mathcal{I}_1 = \left((m_\mu - 2m_\phi)(m_\mu + m_\phi)^2 - 2m_e^2(m_\mu + 2m_\phi)\right)(m_\mu - 2m_\phi)^2$$
$$\mathcal{I}_2 = m_\mu^8 + 7m_\phi^2 m_\mu^6 + 5m_\phi^4 m_\mu^4 - 5m_\phi^6 m_\mu^2 - 2m_\phi^8 - 2m_e^2 m_\mu\, g(m_\mu, m_\phi)\left(m_\mu^4 + 3m_\phi^2 m_\mu^2 + m_\phi^4\right)$$
$$\mathcal{I}_3 = -1680\, m_\mu^{10} - 2240\, m_\phi m_\mu^9 + 4340\, m_\phi^2 m_\mu^8 - 3640\, m_\phi^3 m_\mu^7 - 3122\, m_\phi^4 m_\mu^6 + 504\, m_\phi^5 m_\mu^5$$
$$+ 2639\, m_\phi^6 m_\mu^4 - 402\, m_\phi^7 m_\mu^3 + 73\, m_\phi^8 m_\mu^2 + 70\, m_e^2(24\, m_\mu^6 + 68 m_\phi m_\mu^5 - 104\, m_\phi^2 m_\mu^4 - 6\, m_\phi^3 m_\mu^3$$
$$- 17\, m_\phi^4 m_\mu^2 + 2\, m_\phi^5 m_\mu - m_\phi^6) m_\mu^2 + 6 m_\phi^9 m_\mu - 3\, m_\phi^{10}$$
$$\mathcal{I}_4 = 17\, m_\mu^{12} + 1326\, m_\phi^2 m_\mu^{10} + 3979\, m_\phi^4 m_\mu^8 - 746\, m_\phi^6 m_\mu^6 - 1971\, m_\phi^8 m_\mu^4 - 88\, m_\phi^{10} m_\mu^2 + 3\, m_\phi^{12}$$
$$- 70\, m_\mu^2 m_e^2\left(m_\mu^8 + 28 m_\phi^2 m_\mu^6 - 28\, m_\phi^6 m_\mu^2 - m_\phi^8\right)$$

## Comments about the ALP stability such that it remains undetected within the extent of the collider are in order.

With the only NP interaction that we considered, the ALP decays primarily to a four-body final state containing two electrons and two neutrinos.

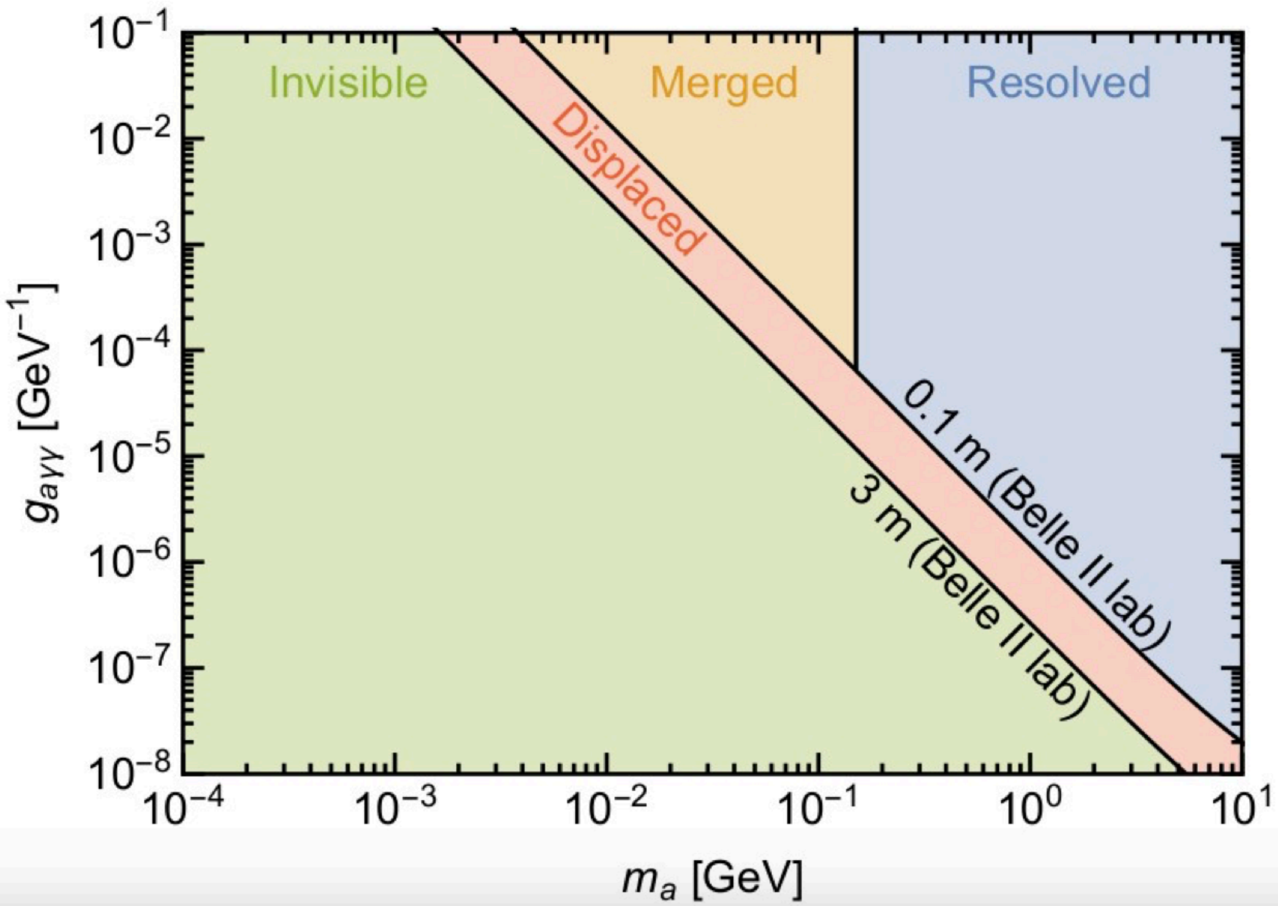
Such a decay width of the ALP to SM fermions is of the order of $10^{-26}$ GeV. Additionally, decay to a pair of electrons is also viable but would then be further loop suppressed. This smallness of the decay width suggests that, within the current set-up, the ALP could very well be considered to be stable within the length of the collider.

From a model-building point of view, this could be achieved by introducing a coupling between the ALP and a dark sector, assuming that this coupling is stronger than the ALP's interactions with the visible sector, as governed by the SU(2) gauge coupling. Although this might be interesting in its own right, exploring the dedicated phenomenology of the dark sector is beyond the scope of the current study.

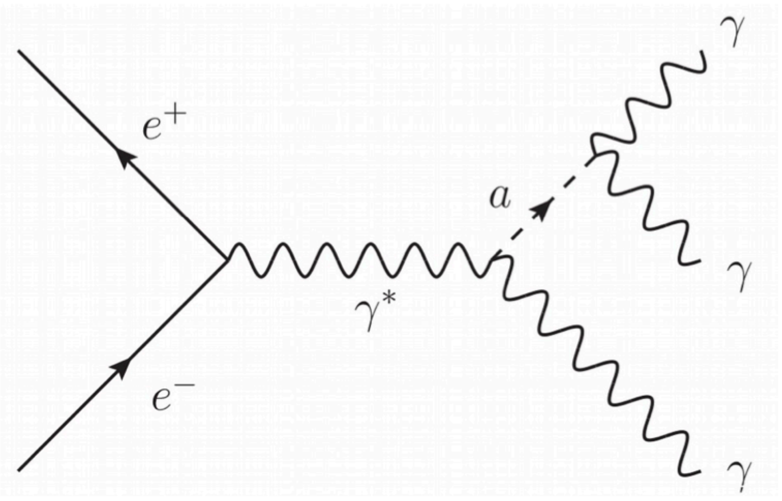
# ALP decay length

- The best experimental strategy depends crucially on the ALP decay length

$$l_a = \beta\,\gamma\,\tau \approx \frac{64\pi\,E_a}{g_{a\gamma}^2\,m_a^4}$$

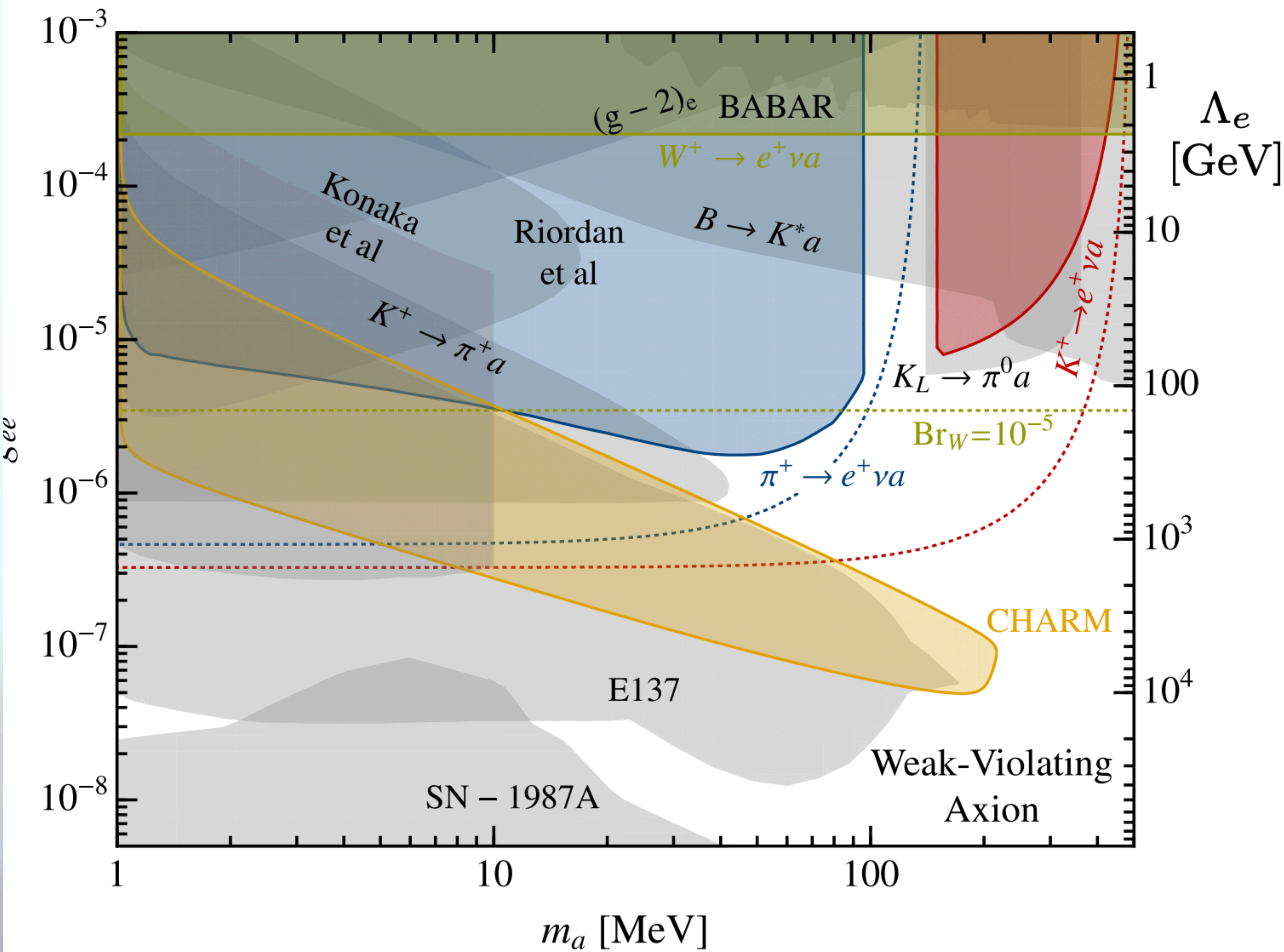



- For example, Belle II is ideally suited for exploring resolved regime (all three photons reconstructed)




- Discrimination from the dominant QED backgrounds can be achieved by searching for a peak in the di-photon invariant mass

# Constraints from Meson Decays and beam-dump experiments for the weak-violating ALPs




Ref: Stefania Gori et al 2022

# Electroweak considerations for the effective operator

Above the regime of Fermi theory, one can start from the gauge-covariant kinetic term in the lepton sector of the SM-Lagrangian

and allow a field-dependent transformation of the lepton doublet as
$\ell_{L/R} \rightarrow \exp\left(ix^i_{L/R}t_i\phi\right)\ell_{L/R}$

In the present setup, with only the left-handed currents associated with W-bosons.
If we start by adding more familiar constructions of ALPs, i.e. $\delta L = \partial_\mu\phi(\bar{\nu}_L\gamma^\mu\nu_L - \bar{l}_L\gamma^\mu l_L)$ then the field redefinition in eliminates this particular operator but gives rise to $\phi(\bar{\mu}\gamma^\nu P_L\nu_\mu)W^-_\nu$ with appropriate coefficients.
One can easily show that the amplitude for observables remains unaltered under this redefinition.
Considering the explicit ALP interaction term in mind, $\delta\mathscr{L} \supset \partial_\mu\phi\, j^\mu$, the most general muon current associated with a light (pseudo)scalar, consists of $\bar{\mu}\gamma^\nu\mu$, $\bar{\mu}\gamma^\nu\gamma_5\mu$ and $\bar{\nu}_\mu\gamma^\nu P_L\nu_\mu$ terms not be independent under electroweak invariance. But, in general, each lepton coupling can arise separately in a weak-invariant theory by including their corresponding currents. After integration by parts of the Lagrangian, we again end up with the term $\phi(\bar{\mu}\gamma^\nu P_L\nu_\mu)W^-_\nu$.
However, note that this four-point interaction would vanish when the general muon current respects the electroweak symmetry. This interaction is independent of $m_\mu$ and may be crucial in constraining the light ALP.

# Electroweak considerations for the effective operator

$\phi$ can be associated with the massive gauge field itself through the $(F_{\mu\nu})^2$ term.
In this case, we can write more familiar SU(2) gauge kinetic term coupling with $\phi$ at d=5 level,

$$\begin{aligned}\mathscr{L} &\supset -\frac{1}{4g_2^2}W^a_{\mu\nu}W^{\mu\nu a} + \frac{1}{4g_2^2}\frac{\kappa}{M}\phi W^a_{\mu\nu}W^{\mu\nu a} \\ &= -\frac{1}{4g_2^2}\left(1-\frac{\kappa}{M}\phi\right)W^a_{\mu\nu}W^{\mu\nu a},\end{aligned}$$

The inclusion of the $\phi W^a_{\mu\nu}W^{\mu\nu a}$ effectively shifts the coupling constant $g_2$ as,

$\frac{1}{g_2^2} \to \frac{1}{g_2^2}\left(1-\frac{\kappa}{M}\phi\right)$. We can once again rescale the massive gauge terms: $W^a_\mu \to g_2 W^a_\mu$. Using equations of motion, we can express the gauge field $W_{\mu}^a$ up to order $\mathcal{O}(1/m_W^2)$ as,
$W^a_\mu \simeq \frac{g_2'}{m_W^2}(\bar{\psi}\gamma_\mu t^a \psi)$. Subsequently, the effective operator after integrating out the massive gauge boson terms becomes,

$$\mathscr{L} \supset \frac{g_2^2}{2m_W^2}\left(1+\frac{\kappa}{M}\phi\right)(\bar{\psi}\gamma_\mu t^a\psi)(\bar{\psi}\gamma^\mu t^a\psi)\,.$$

The low energy effective muon decay operator in the Standard Model has a coefficient $G_F \sim \frac{g_2^2}{m_W^2}$.
The inclusion of the $\phi$ field along with the heavy messenger field gives a correction to this coefficient $G_F$, either as a correction to $g_2$ or to $m_W$. The correction to the masses $m_W$ of the $SU(2)$ gauge fields could occur in models where the messenger field is an SM complex scalar acquiring vacuum expectation value.

# Electroweak considerations for the effective operator

Another possible UV scenario which results in this kind of EFT is to design a scalar potential (using only marginal and relevant operators) with the $\phi$ field and the doublet Higgs field as,

$$V(H,\phi) \ = -\mu^2(H^\dagger H) + \lambda(H^\dagger H)^2 - y\phi H^\dagger H$$

Note that, this potential is just a simplest example and falls under the multitude of hidden sector Higgs-portal scenarios.

The minimum of the potential is found at a finite value, which is shifted from the original vacuum expectation value and linearly depends on $\phi$. We find that the replacement of the EW vev (and therefore of $G_F$) by its $\phi$ - dependent value allows us to re-derive the low energy EFT.

Thus we see how the effective four-fermion-scalar operator could possibly be generated from higher dimensional irrelevant operators and can be used for the low-energy effective study that we perform. Further considerations regarding EW T-parameter and/or flavour considerations rely on the specifics of a concrete UV model and are beyond the scope of this study.