Università di Genova | Dipartimento di Fisica

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Lepton-flavour-violating decays into axion-like particles

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Mainly based on work in progress with
D. Redigolo, R. Ziegler, and J. Zupan

Neutrino masses/oscillations $\Longleftrightarrow \not{L}_e, \not{L}_\mu, \not{L}_\tau$

Lepton family numbers are not conserved:

why not $\mu \to e\gamma, \quad \tau \to \mu\gamma, \quad \mu \to eee, \text{ etc.}\,?$

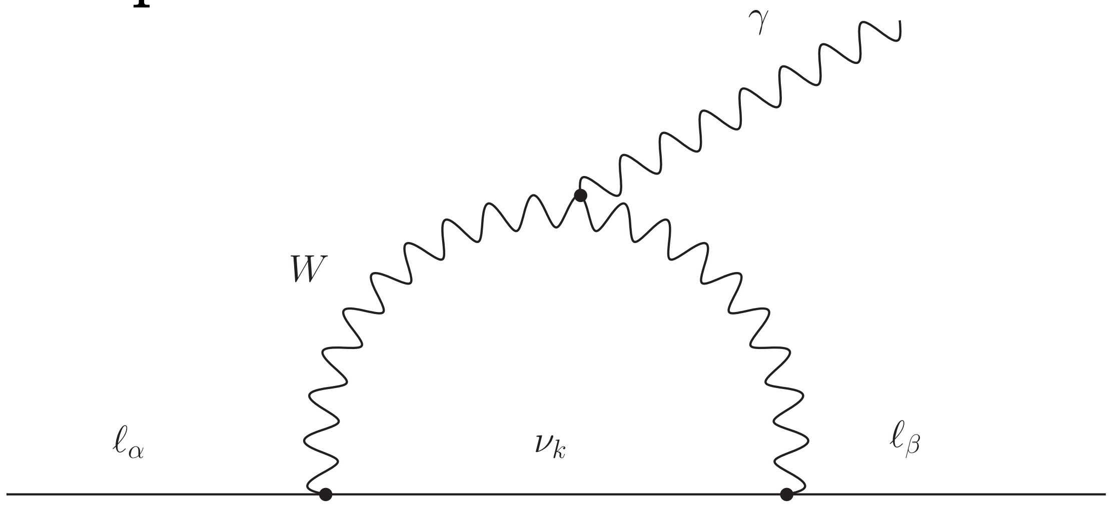
Why are we searching for CLFV?

- Neutrinos oscillate → Lepton family numbers are not conserved!

- Neutrino mass eigenstates couple to charged leptons of different flavours through the PMNS

- In the SM + massive neutrinos:

$$\frac{\Gamma(\ell_\alpha \to \ell_\beta \gamma)}{\Gamma(\ell_\alpha \to \ell_\beta \nu \bar{\nu})} = \frac{3\alpha}{32\pi} \left| \sum_{k=1,3} U_{\alpha k} U^*_{\beta k} \frac{m^2_{\nu_k}}{M^2_W} \right|^2$$



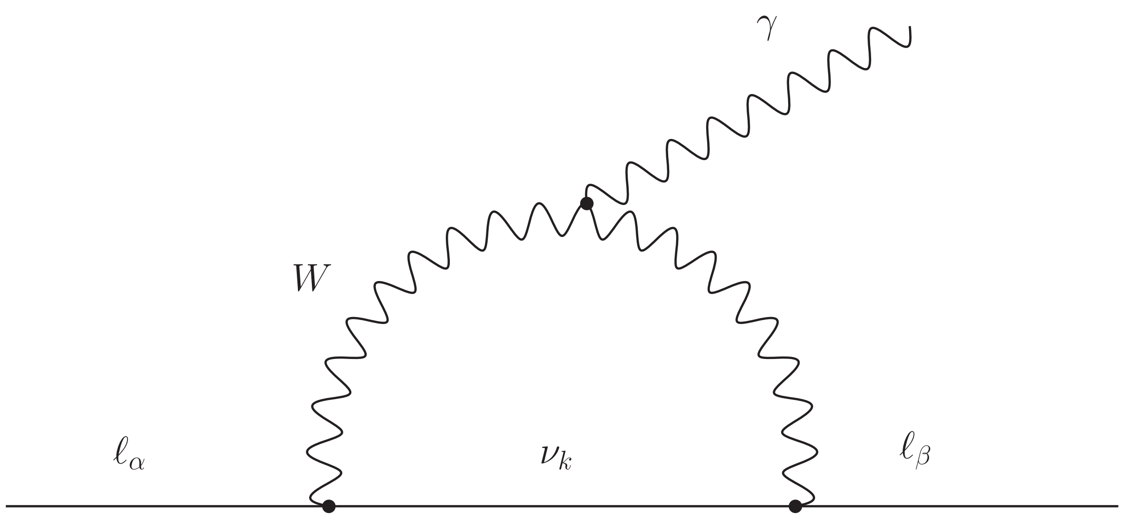
Cheng Li '77, '80; Petcov '77

⇨ $\text{BR}(\mu \to e\gamma) \approx \text{BR}(\tau \to e\gamma) \approx \text{BR}(\tau \to \mu\gamma) = 10^{-55} \div 10^{-54}$

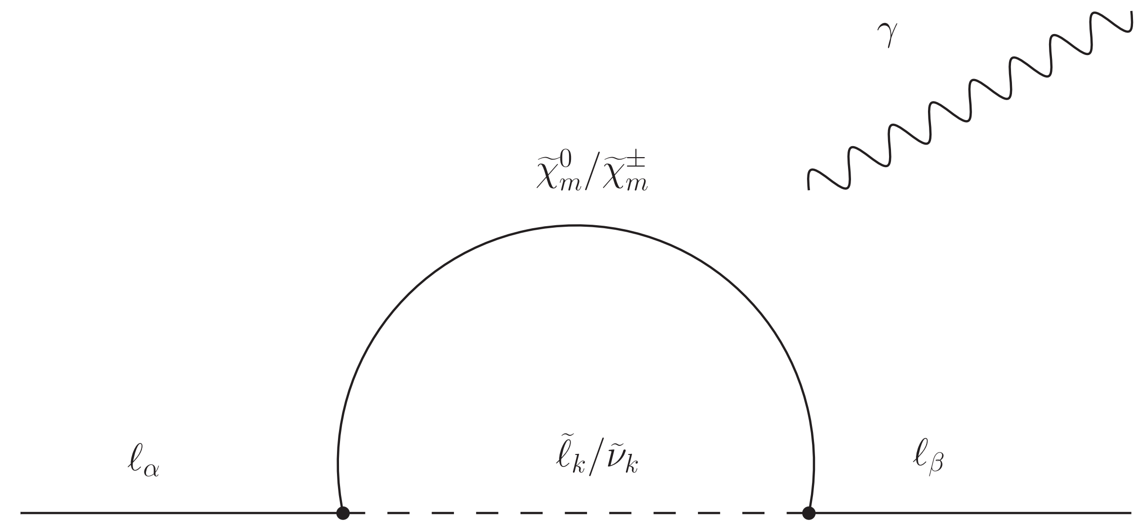
Large mixing, but huge suppression due to small neutrino masses

⇨ In presence of NP at the TeV we can expect large effects

Why are we searching for CLFV?



e.g. SUSY



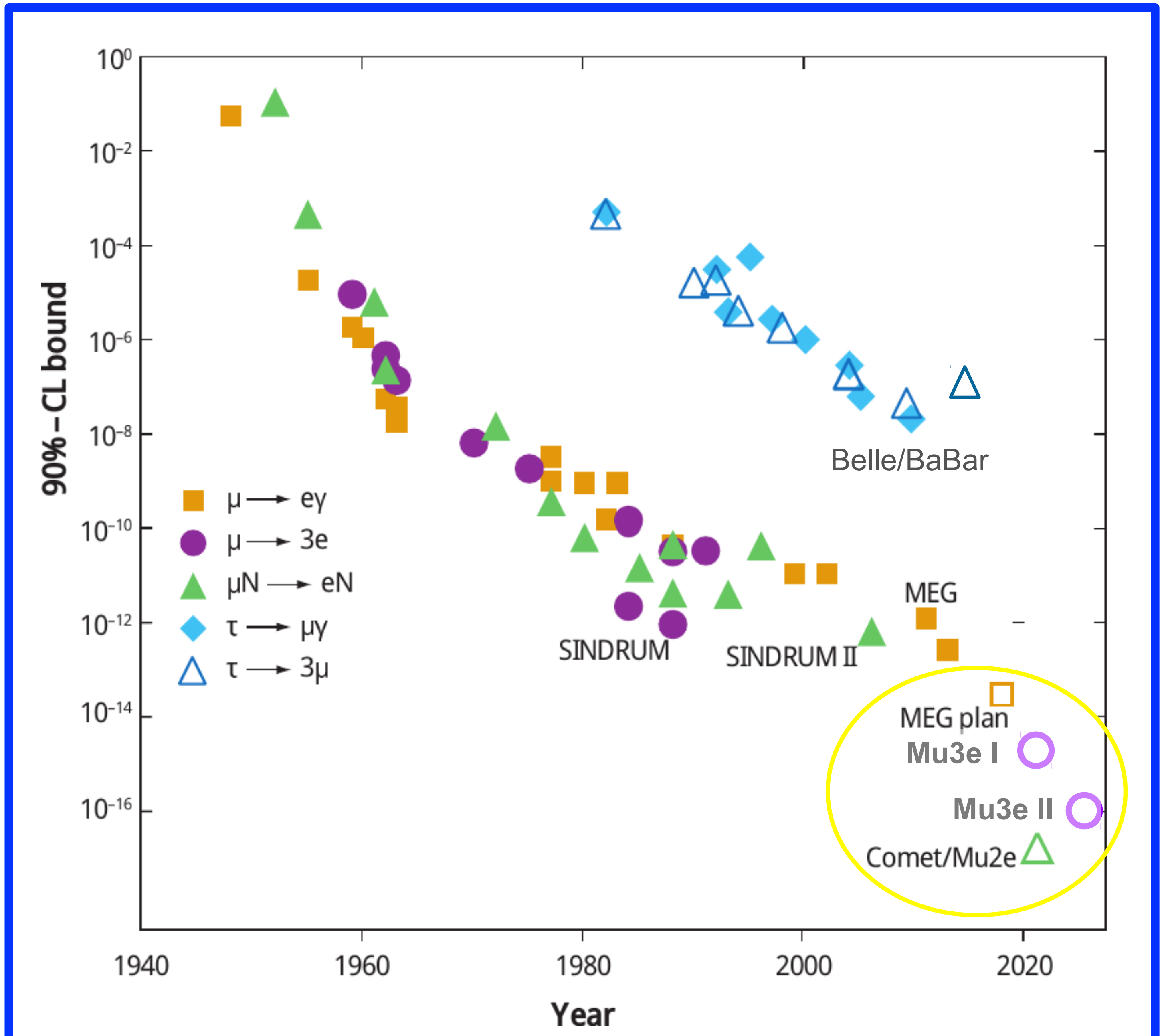
Borzumati Masiero ‘86;
Hisano et al. ‘95

$$\frac{\Gamma(\ell_\alpha \to \ell_\beta \gamma)}{\Gamma(\ell_\alpha \to \ell_\beta \nu \bar{\nu})} = \frac{3\alpha}{32\pi} \left| \sum_{k=1,3} U_{\alpha k} U^*_{\beta k} \frac{m^2_{\nu_k}}{M^2_W} \right|^2$$

$$\frac{\Gamma(\ell_\alpha \to \ell_\beta \gamma)}{\Gamma(\ell_\alpha \to \ell_\beta \nu \bar{\nu})} \sim \frac{|\delta_{\alpha\beta}|^2}{G_F^2\, m^4_{\mathrm{SUSY}}}$$

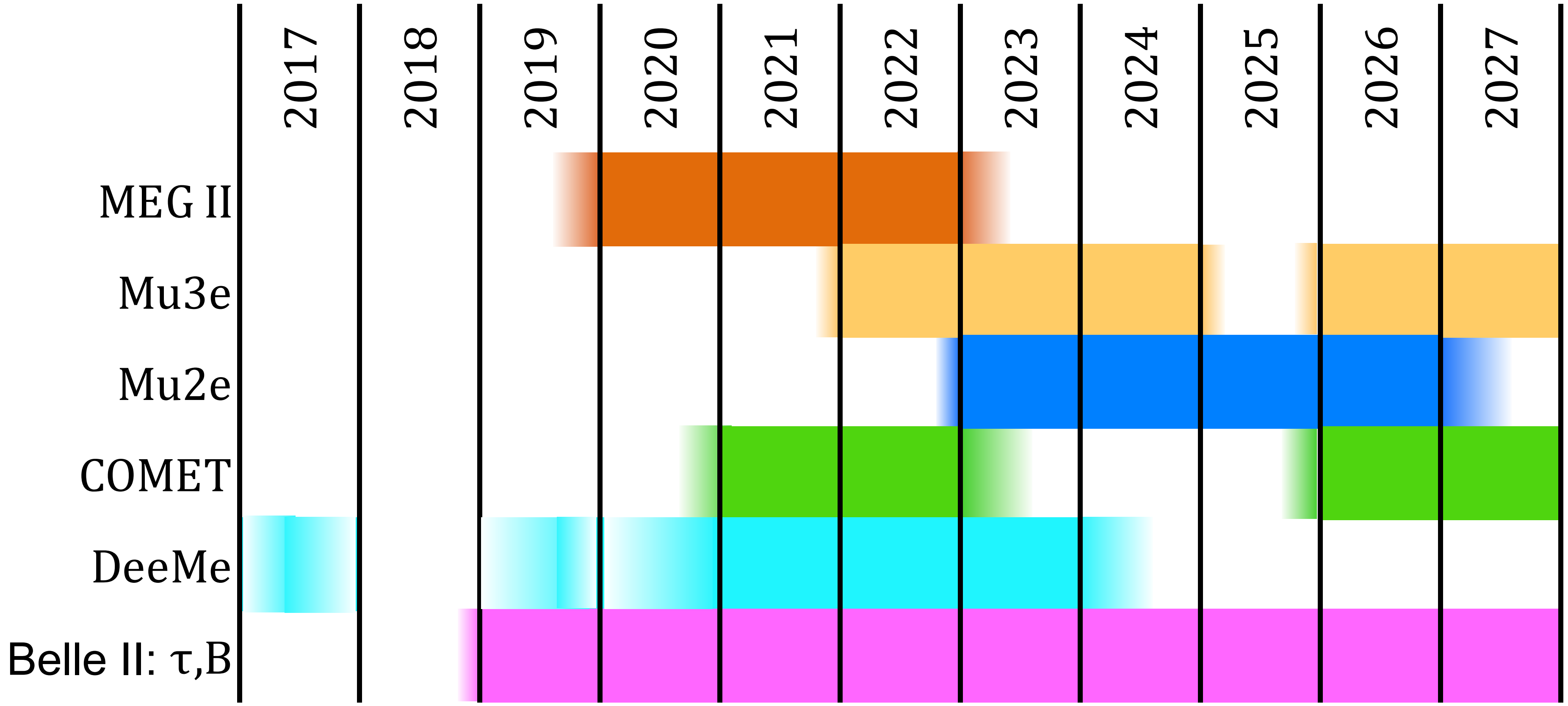
- Unambiguous signal of New Physics
- Stringent test of NP coupling to leptons
- It probes scales far beyond the LHC reach

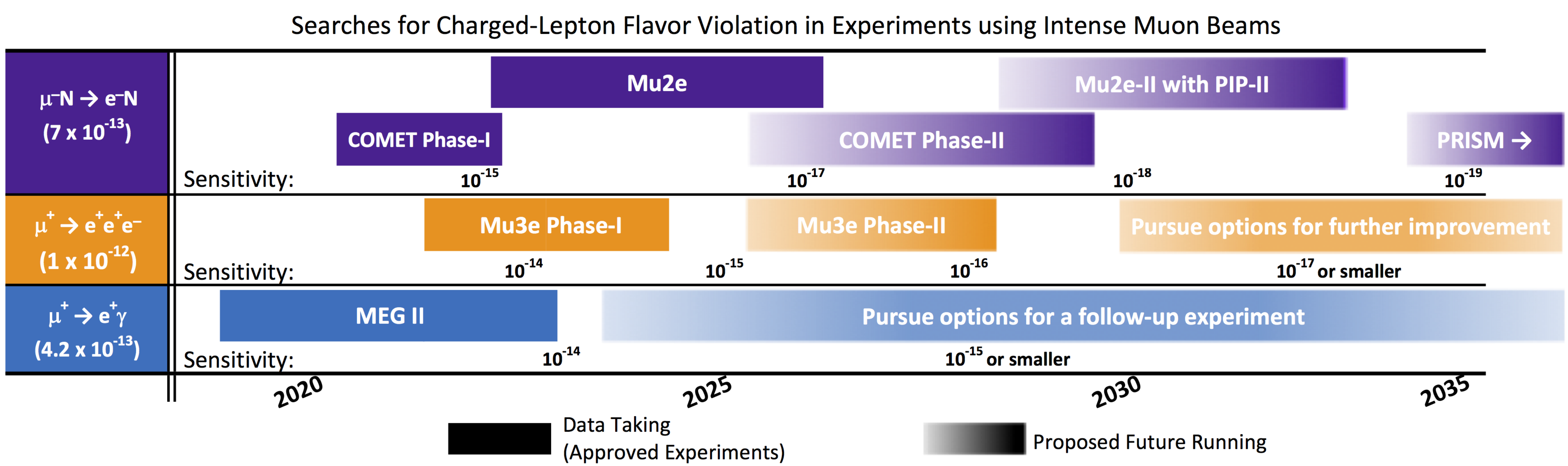
… and we have experiments



Sought for more than 70 years…

… and we have experiments





Definitely worth to keep searching, but…

What if we haven't looked (enough) in the right place?

Assume there is a *light*, *invisible*, new particle "a" with *FV couplings* to leptons

Light:

$$m_a < m_\mu\,,\ m_\tau$$

Invisible:

- Neutral
- Feebly coupled (long-lived)

CLFV modes would then be $\mu \to e\,a,\ \ \tau \to \mu\,a,\ \ \mu \to e\,\gamma\,a,\ \ \text{etc}\,.$

Interesting interplay with cosmo/astro:

- DM candidate? (if long-lived enough)
- Bounds from star cooling/supernovae (if light and feeble enough)

Why should a be light and feebly-coupled?

That's natural, if it is the (pseudo) Nambu-Goldstone boson (PNGB) of a broken global U(1), *aka* an axion-like particle (ALP)

Examples:

Global symmetry:	PNGB:
• Lepton Number	Majoron
• Peccei-Quinn	Axion
• Flavour symmetry	Familon
…	

Wilczek '82

Pilaftsis '93

Feng et al. '97

LC Goertz Redigolo Ziegler Zupan '16

Di Luzio et al. '17, '19

…

Equivalent possibility: light Z' of a local U(1), e.g. L_i-L_j (with $g \ll 1$)

Heeck '16

General couplings to leptons:

$$\mathcal{L}_{a\ell\ell} = \frac{\partial^\mu a}{2 f_a} \left(C^V_{ij}\ \bar{\ell}_i \gamma_\mu \ell_j + C^A_{ij}\ \bar{\ell}_i \gamma_\mu \gamma_5 \ell_j \right)$$

General couplings to leptons:

Shift symmetry (PNGB!) → m_a from (small) explicit U(1) breaking

$$\mathcal{L}_{a\ell\ell} = \frac{\partial^\mu a}{2 f_a} \left(C^V_{ij} \; \bar{\ell}_i \gamma_\mu \ell_j + C^A_{ij} \; \bar{\ell}_i \gamma_\mu \gamma_5 \ell_j \right)$$

U(1)-breaking scale → coupling suppression

General couplings to leptons:

$$\mathcal{L}_{a\ell\ell} = \frac{\partial^\mu a}{2 f_a} \left(C^V_{ij} \; \bar{\ell}_i \gamma_\mu \ell_j + C^A_{ij} \; \bar{\ell}_i \gamma_\mu \gamma_5 \ell_j \right)$$

Where does *lepton flavour violation* come from?

- If lepton U(1) charges are flavour non-universal ⇨ naturally flavour-violating couplings
- Alternatively, loop-induced flavour-violating couplings

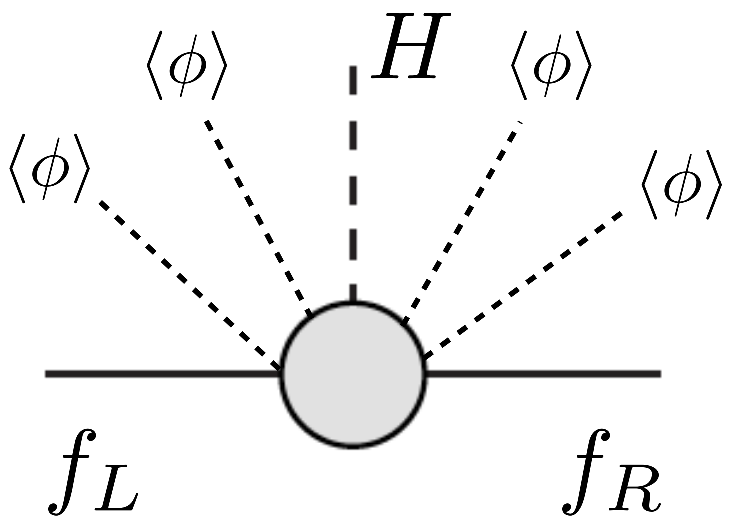
Two explicit examples following…

Froggatt-Nielsen flavour models

- SM fermions charged under a new horizontal symmetry G_F
- G_F forbids Yukawa couplings at the renormalisable level
- G_F spontaneously broken by the vev(s) of one or more scalars (the "flavons")
- Yukawas arise as higher dimensional operators

Froggatt Nielsen '79
Leurer Seiberg Nir '92, '93
...

$$\mathcal{L}_{\text{Yuk.}} = \left(\frac{\langle\phi\rangle}{M}\right)^{n^f_{ij}} \bar{f}_{L\,i} f_{R\,j} H$$



$\langle\phi\rangle < M$ ⟹ $\epsilon \equiv \langle\phi\rangle/M$ small expansion parameter (M=UV scale)

n^f_{ij} dictated by the symmetry

G_F could abelian or non-abelian, continuous or discrete, local or *global*

Froggatt-Nielsen U(1)

Quark sector

	ϕ	$\bar{q}_i$	u_i	d_i	h
U(1)	-1	$[q]_i$	$[u]_i$	$[d]_i$	0

$\Rightarrow$

$$y^u_{ij} = a^u_{ij}\, \epsilon^{[q]_i+[u]_j}$$
$$y^d_{ij} = a^d_{ij}\, \epsilon^{[q]_i+[d]_j}$$

Rotation matrices $V_L^{f\dagger} Y^f V_R^f = Y^f_{diag}$ $\Rightarrow$ $(V_L^{u,d})_{ij} \approx \epsilon^{|[q]_i-[q]_j|}$ $\quad (V_R^{u,d})_{ij} \approx \epsilon^{|[u,d]_i-[u,d]_j|}$

Successful predictions for $V^{\rm CKM} = V^u V^{d\dagger}$

$$V_{ud} \approx V_{cs} \approx V_{tb} \approx 1 \qquad V_{ub} \approx V_{td} \approx V_{us} \times V_{cb}$$

(independent of charge assignment)

Example:

$$([q]_1,\,[q]_2,\,[q]_3) = (3,2,0) \quad ([u]_1,\,[u]_2,\,[u]_3) = (5,2,0) \quad ([d]_1,\,[d]_2,\,[d]_3) = (4,2,2)$$

$$Y_u \sim \begin{pmatrix} \epsilon^8 & \epsilon^5 & \epsilon^3 \\ \epsilon^7 & \epsilon^4 & \epsilon^2 \\ \epsilon^5 & \epsilon^2 & 1 \end{pmatrix} \qquad Y_d \sim \begin{pmatrix} \epsilon^7 & \epsilon^5 & \epsilon^5 \\ \epsilon^6 & \epsilon^4 & \epsilon^4 \\ \epsilon^4 & \epsilon^2 & \epsilon^2 \end{pmatrix}$$

$$\epsilon = \langle \phi \rangle / M \approx 0.23$$

Lepton sector

	ϕ	$\bar{L}_i$	e_i	h
U(1)	-1	$[L]_i$	$[e]_i$	0

$\Rightarrow$

$$y^e_{ij} = a^e_{ij} \left(\frac{\langle\Phi\rangle}{M}\right)^{[L]_i+[e]_j}$$

$$m^\nu_{ij} = \kappa^\nu_{ij} \frac{v^2}{\Lambda_N} \left(\frac{\langle\Phi\rangle}{M}\right)^{[L]_i+[L]_j}$$

LH charges can chosen to give a (quasi-)anarchical PMNS

RH charges then responsible for charged leptons hierarchy

Examples:

Altarelli Feruglio Masina Merlo '12

- Anarchy $([L]_1,\ [L]_2,\ [L]_3) = ([L], [L], [L])$
- Mu-tau anarchy $([L]_1,\ [L]_2,\ [L]_3) = ([L]+1, [L], [L])$
- Hierarchy $([L]_1,\ [L]_2,\ [L]_3) = ([L]+2, [L]+1, [L])$

Charged lepton hierarchy: $([e]_1,\ [e]_2,\ [e]_3) = (8-[L]_1, 4-[L]_2, 2-[L]_3)$
(with $\epsilon \approx 0.2$)

Froggatt-Nielsen U(1)

Lepton sector

	ϕ	$\bar{L}_i$	e_i	h
U(1)	-1	$[L]_i$	$[e]_i$	0

$\Rightarrow$

$$y^e_{ij} = a^e_{ij}\left(\frac{\langle\Phi\rangle}{M}\right)^{[L]_i+[e]_j}$$

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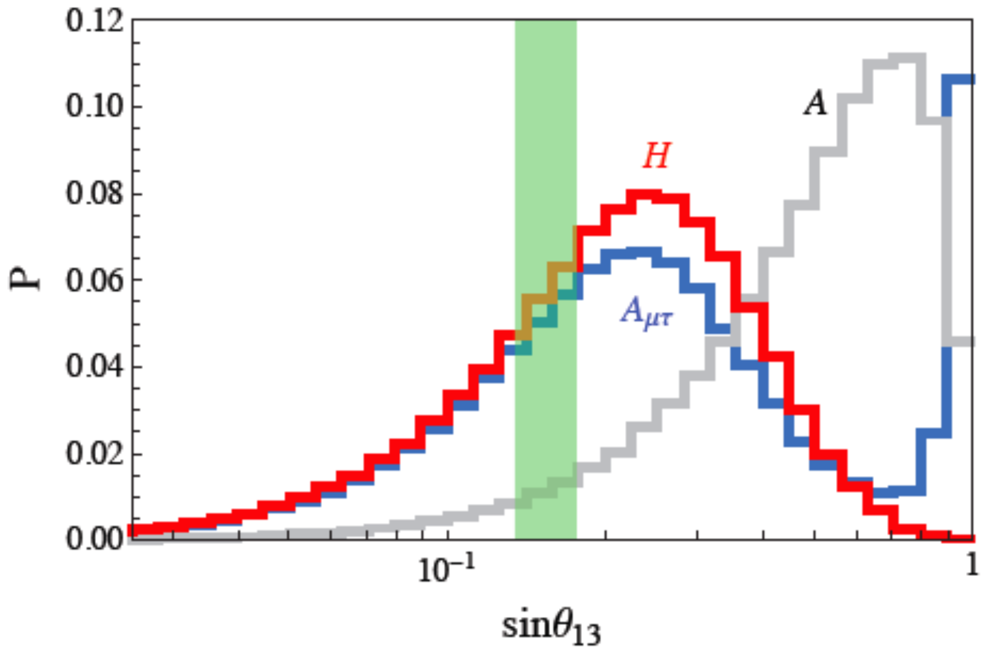
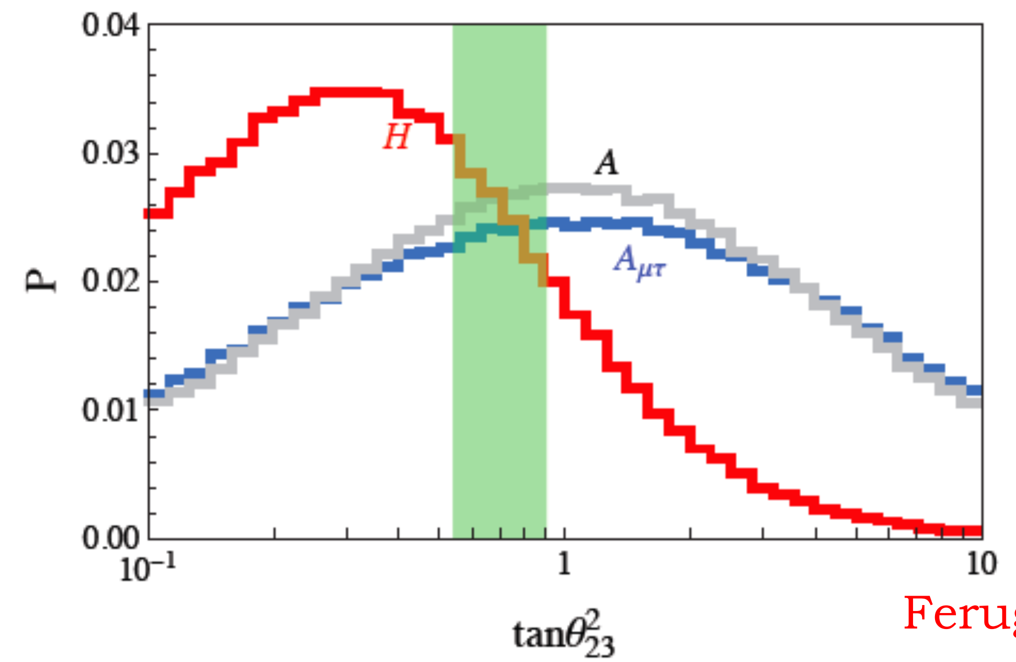
Examples:





Feruglio '17

Leptonic FN "familon"

PNGB of a spontaneously-broken leptonic FN U(1)

$$\phi = \frac{1}{\sqrt{2}}(f+\rho_\phi)e^{ia/f} \Rightarrow \mathcal{L}_{aff} = \frac{\partial^\mu a}{f}\left(C_V^{ij}\,\bar{\ell}_i\gamma_\mu\ell_j + C_A^{ij}\,\bar{\ell}_i\gamma_\mu\gamma_5\ell_j\right)$$

$$C_{V/A} = V_R^\dagger X_R V_R \pm V_L^\dagger X_L V_L$$

L and R rotations to the lepton mass basis

$U(1)_{FN}$ charges

$$X_R = \begin{pmatrix} [e]_1 & & \\ & [e]_2 & \\ & & [e]_3 \end{pmatrix} \quad X_L = \begin{pmatrix} [L]_1 & & \\ & [L]_2 & \\ & & [L]_3 \end{pmatrix}$$

$$V_L^\dagger Y^e V_R = Y^e_{diag}$$

$$(V_L)_{ij} \approx \epsilon^{|[L]_i-[L]_j|}, \quad (V_R)_{ij} \approx \epsilon^{|[e]_i-[e]_j|}$$

flavour non-universal charges
→ flavour-violating couplings

Lepton-flavour-violating decays into an (invisible) PNGB:

$$\mu\to ea \qquad \tau\to ea \qquad \tau\to\mu a$$

$$\Gamma(\ell_i\to\ell_j a) = \frac{1}{16\pi}\frac{m_{\ell_i}^3}{f^2}\left(|C_V^{ij}|^2+|C_A^{ij}|^2\right)\left(1-\frac{m_a^2}{m_{\ell_i}^2}\right)^2$$

Type I seesaw: $\mathcal{L} = \mathcal{L}_{\rm SM} + i\overline{N}\partial\!\!\!/ N - \left(Y_N \overline{N}\widetilde{\Phi}^\dagger L + \frac{1}{2} M_N \overline{N} N^c + \text{h.c.} \right)$

L-breaking term

$$\mathcal{M}_\nu = \begin{pmatrix} 0 & Y_N^T v/\sqrt{2} \\ Y_N v/\sqrt{2} & M_N \end{pmatrix} \overset{M_N \gg Y_N v}{\Longrightarrow} m_\nu = -\frac{v^2}{2} Y_N^T M_N^{-1} Y_N$$

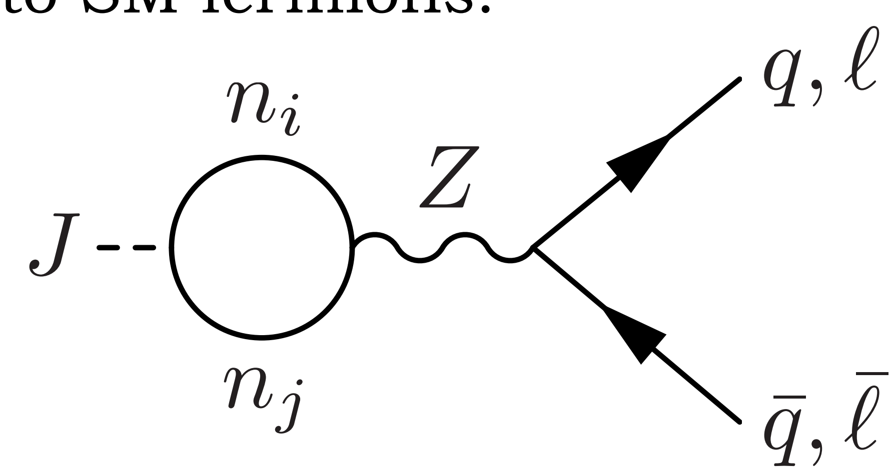
Spontaneous breaking of the lepton number:

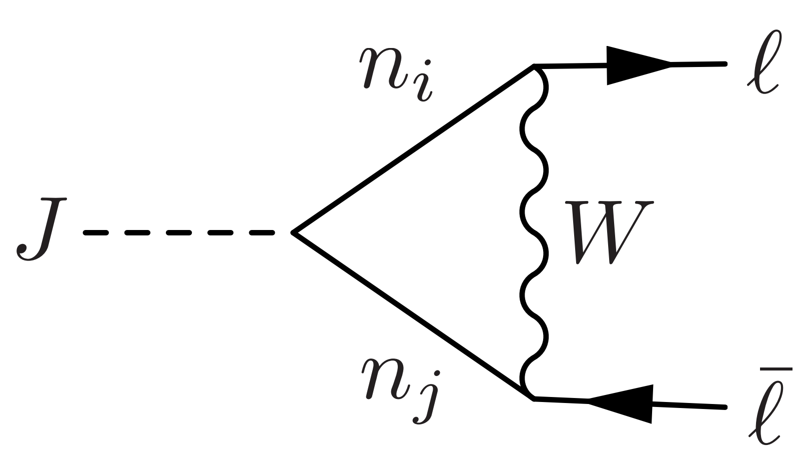
$$\sigma = \frac{f_N + \hat{\sigma}}{\sqrt{2}} e^{iJ/f_N} \Longrightarrow M_N = \lambda_N f_N/\sqrt{2}$$

PNGB: Majoron!

Chikashige Mohapatra Peccei ‘80

Couplings to SM fermions:





Majoron

Type I seesaw: $\mathcal{L} = \mathcal{L}_{\rm SM} + i\overline{N}\partial\!\!\!/ N - \left(Y_N \overline{N}\widetilde{\Phi}^\dagger L + \frac{1}{2} M_N \overline{N} N^c + \text{h.c.} \right)$

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PNGB: Majoron!

Chikashige Mohapatra Peccei '80

Couplings to SM fermions:

$$C^V_{q_i q_j} = 0\,, \qquad C^A_{q_i q_j} = -\frac{T_3^q}{16\pi^2}\delta_{ij}\,\text{Tr}\left(Y_N Y_N^\dagger\right)\,,$$

$$C^V_{\ell_i \ell_j} = \frac{1}{16\pi^2}\left(Y_N Y_N^\dagger\right)_{ij}\,, \qquad C^A_{\ell_i \ell_j} = \frac{1}{16\pi^2}\left[\frac{\delta_{ij}}{2}\text{Tr}\left(Y_N Y_N^\dagger\right) - (Y_N Y_N^\dagger)_{ij}\right]$$

Generically flavour-violating, (V-A)

Pilaftsis '94
Garcia-Cely Heeck '17

$$\mathcal{L}_{a\ell\ell} = \frac{\partial^\mu a}{2 f_a} \left(C_{ij}^V \, \bar{\ell}_i \gamma_\mu \ell_j + C_{ij}^A \, \bar{\ell}_i \gamma_\mu \gamma_5 \ell_j \right)$$

This generic Lagrangian induces 2-body LFV decays such as:

$$\Gamma(\ell_i \to \ell_j \, a) = \frac{1}{16\pi} \frac{m_{\ell_i}^3}{F_{ij}^2} \left(1 - \frac{m_a^2}{m_{\ell_i}^2} \right)^2 \qquad F_{ij} \equiv \frac{2 f_a}{\sqrt{|C_{ij}^V|^2 + |C_{ij}^A|^2}}$$

Feng et al. '97

Goal: constrain the effective LFV scales F_{ij} using experimental data

- Which experiments?
- What are the future prospects?

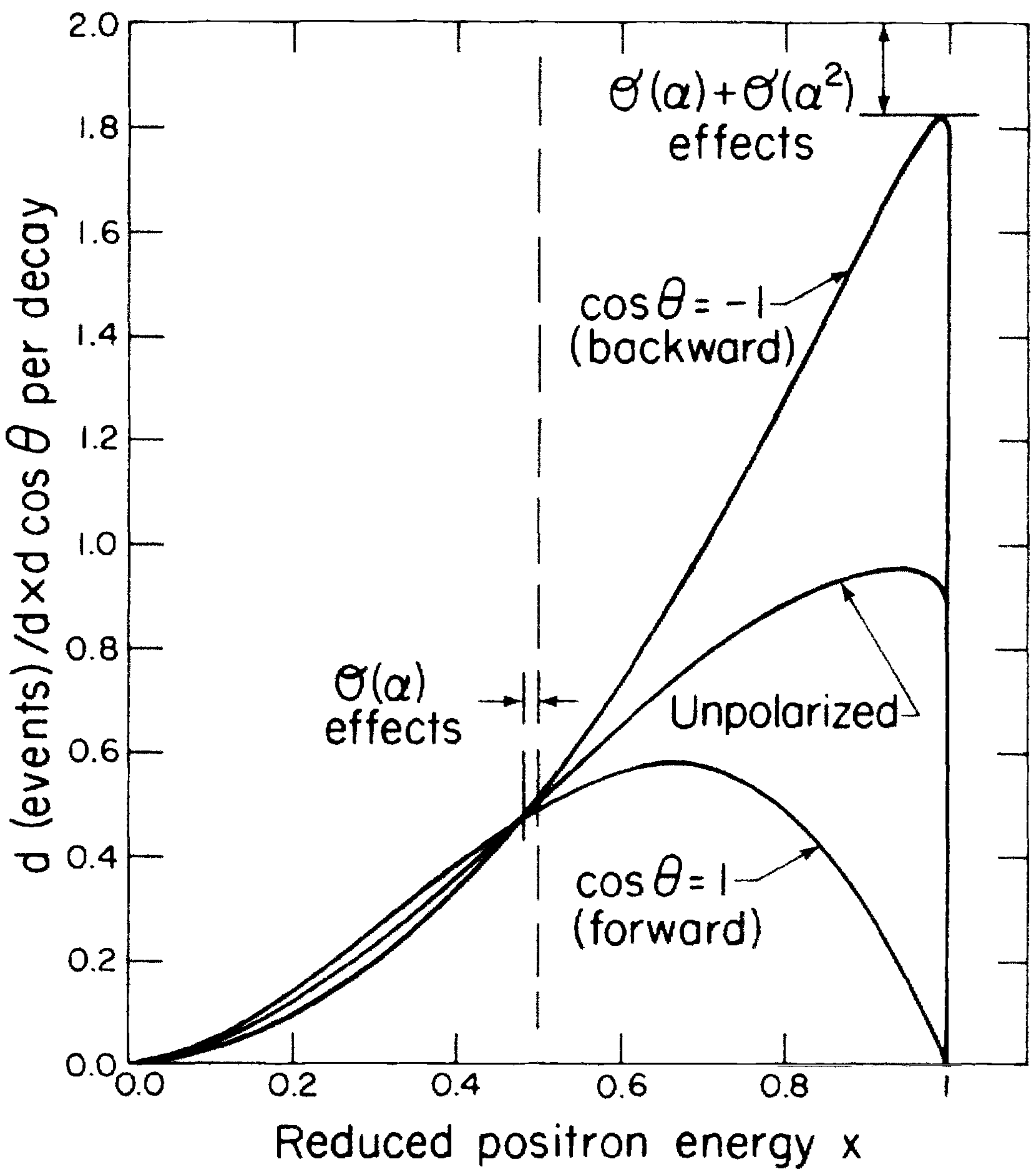
- Jodidio et al. (TRIUMF) 1986

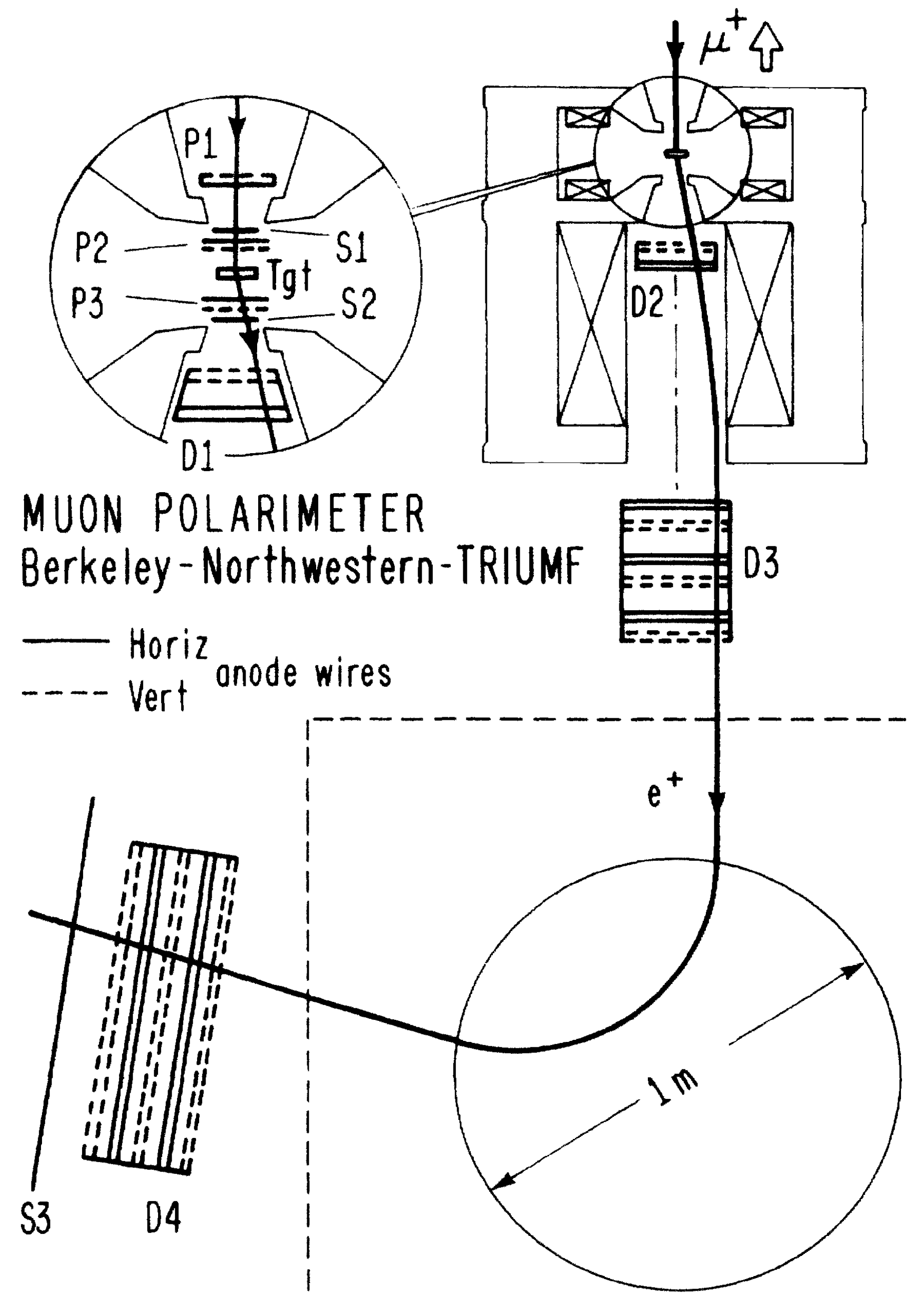
Search for RH currents with $1.8{\times}10^7$ polarized μ^+

Ordinary $\mu \to e\bar{\nu}\nu$

$$\frac{d^2\Gamma}{dx\, d\cos\theta} = \Gamma_\mu \left((3-2x) - P(2x-1)\cos\theta\right) x^2$$

$$x = 2E_e/m_\mu$$





Very good e+ momentum resolution
(~70 KeV at the e.p.)

Past searches: $\mu \to e\, a$

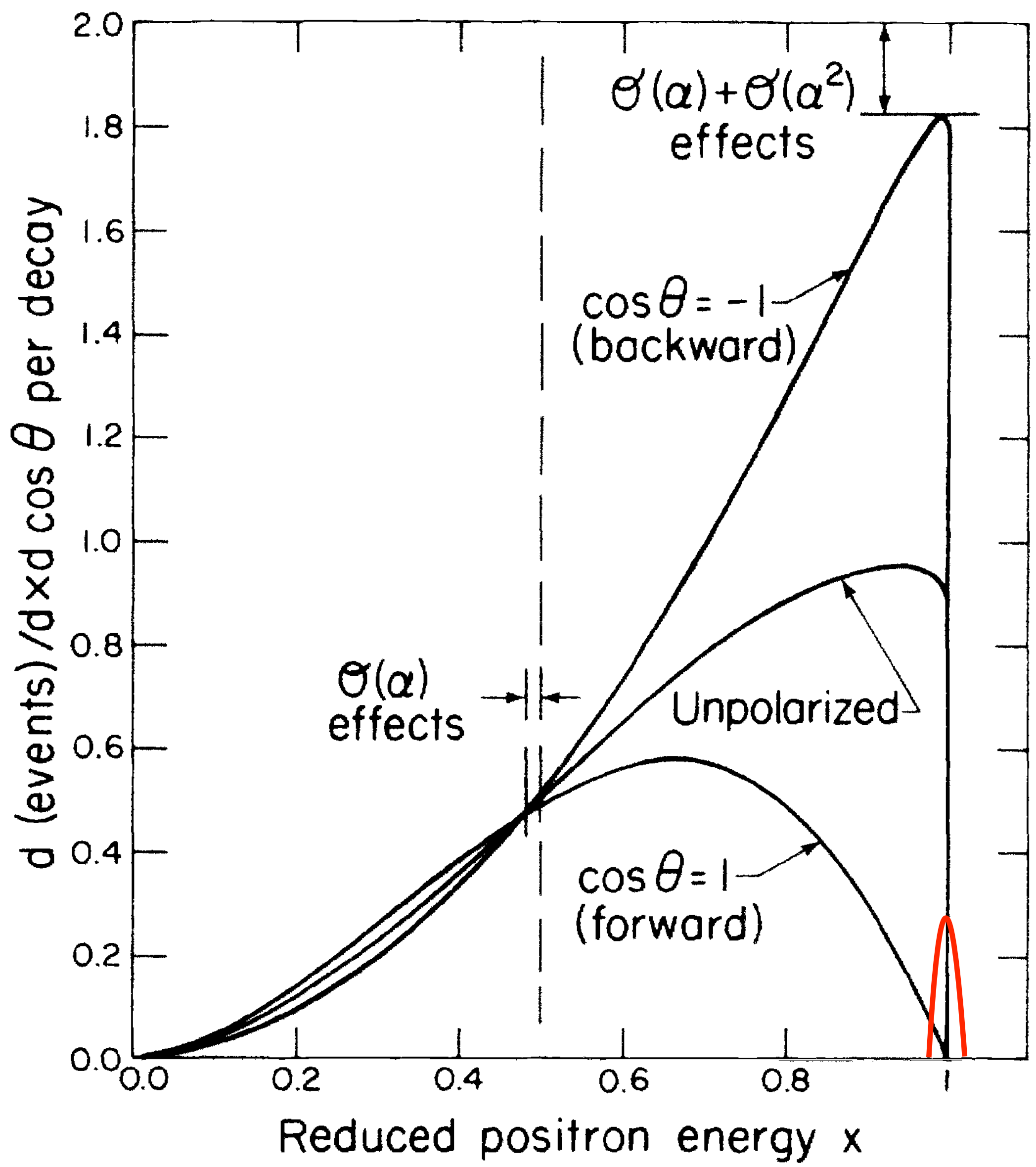
- Jodidio et al. (TRIUMF) 1986

Search for RH currents with 1.8×10^7 polarized μ^+ interpreted in terms of $\mu \to ea$ too

Ordinary $\mu \to e\bar{\nu}\nu$

$$\frac{d^2\Gamma}{dx\, d\cos\theta} = \Gamma_\mu \left((3-2x) - P(2x-1)\cos\theta\right) x^2$$

$$x = 2E_e/m_\mu$$



$\mu \to e\, a$ signal for $m_a \approx 0$:

monochromatic e^+ at $m_\mu/2$

Unless it couples (V-A) like in the SM:

$$\frac{d\Gamma(\mu^+ \to e^+ a)}{d\cos\theta} = \frac{\Gamma_{\mu\to e\, a}}{2}\left[1 + 2P\cos\theta \frac{C^V_{e\mu} C^A_{e\mu}}{(C^V_{e\mu})^2 + (C^A_{e\mu})^2}\right]$$

for the *isotropic* case, they set the limit

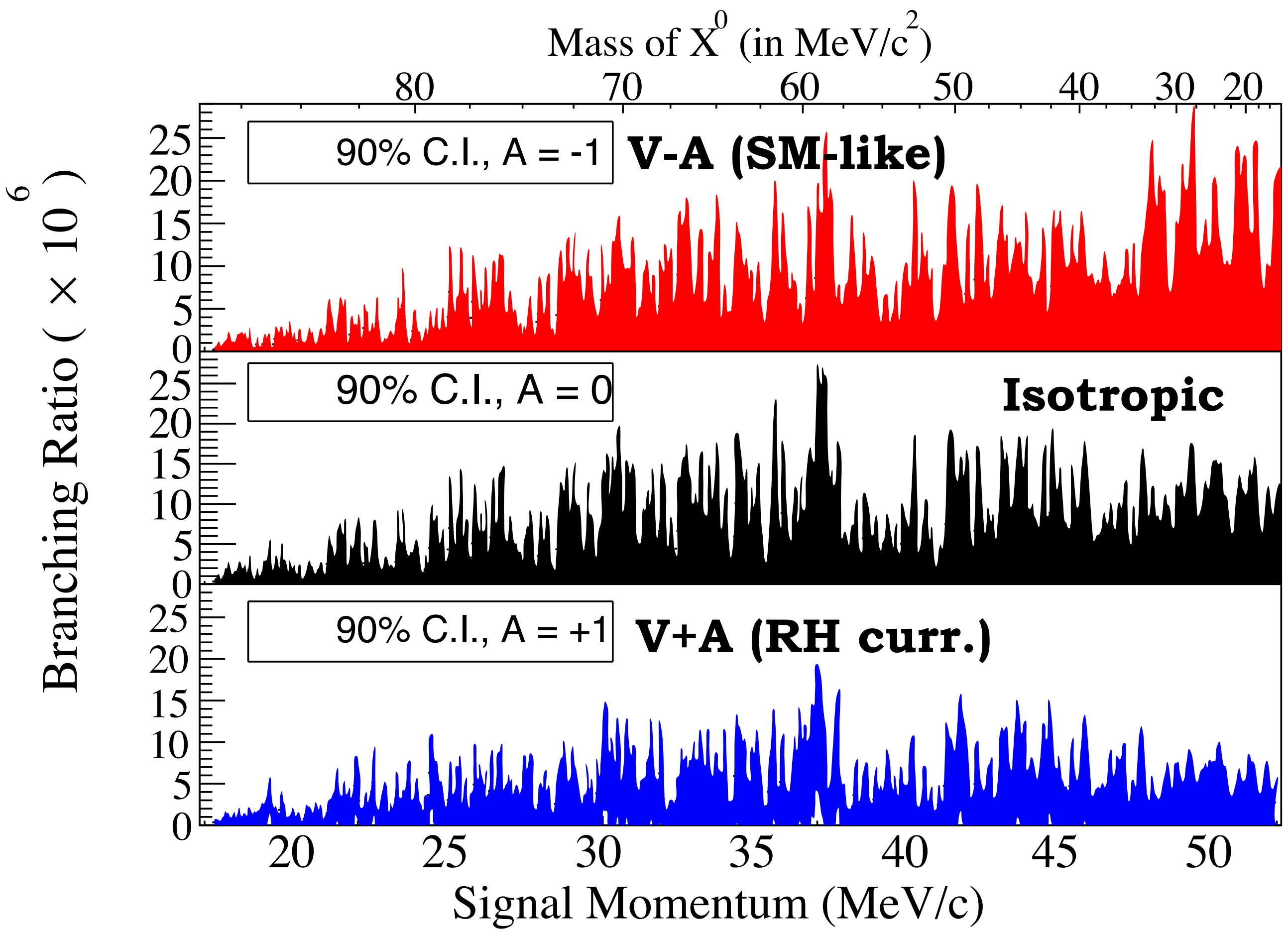
$$\Rightarrow \quad \mathrm{BR}(\mu^+ \to e^+ a) < 2.6 \times 10^{-6}$$

thus one gets

$$\Rightarrow \quad F_{e\mu} \; > \; 5.5 \times 10^9 \text{ GeV}$$

- TWIST 2014 Precise measurement of Michel parameters plus dedicated search for $\mu \to ea$ in the whole m_a range considering anisotropy of the signal

Limits (with $5.8{\times}10^8$ μ^+):



Decay Signal		90% C.L. (in ppm)	p-value
$A = 0$	Average	9	
	$p = 37.03$ MeV/c	26	0.66
	Endpoint	21	0.81
$A = -1$ SM-like	Average	10	
	$p = 37.28$ MeV/c	26	0.60
	Endpoint	58	0.80
$A = +1$	Average	6	
	$p = 19.13$ MeV/c	6	0.59
	Endpoint	10	0.90

For V-A coupl. and $m_a \approx 0$: $\mathrm{BR}(\mu \to ea) < 5.8 \times 10^{-5}$

$$\Rightarrow \quad F_{e\mu} > 1.2 \times 10^9\ \mathrm{GeV}$$

- Crystal Box 1988

PHYSICAL REVIEW D VOLUME 38, NUMBER 7 1 OCTOBER 1988

Search for rare muon decays with the Crystal Box detector

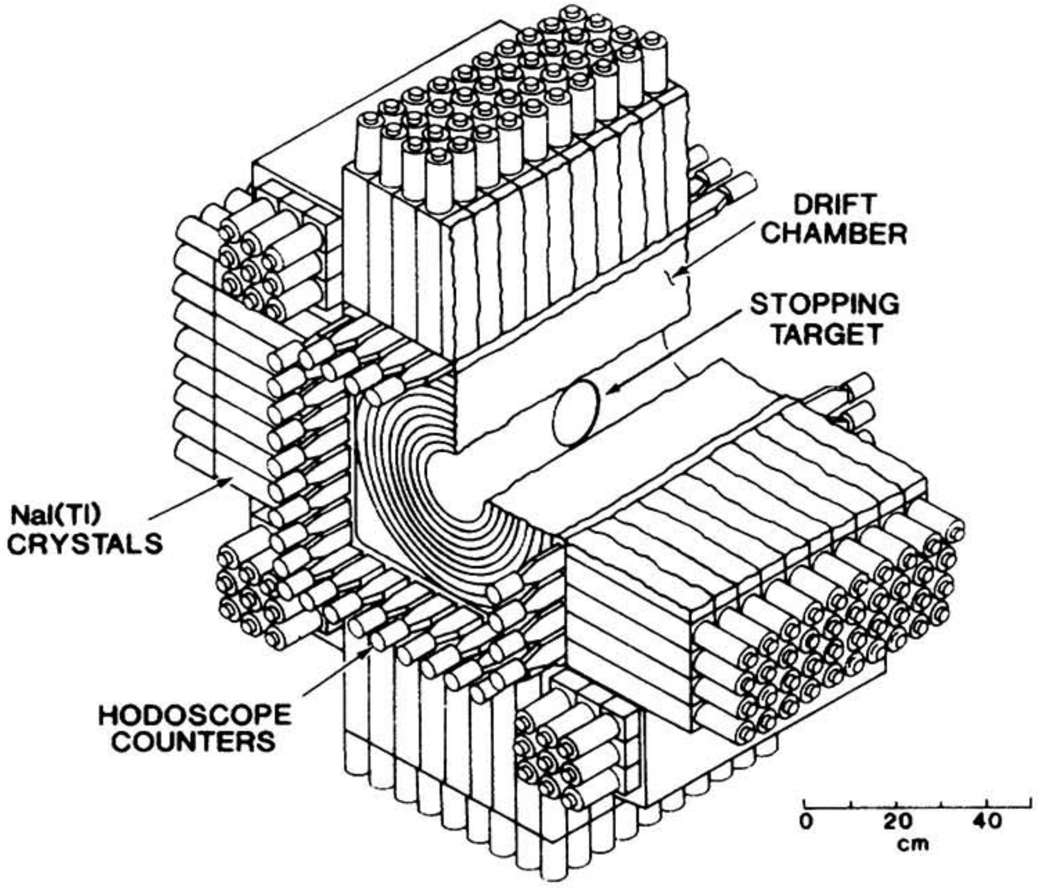


TABLE I. Types of events generated with the Monte Carlo program.

Process	Trigger
$\mu^+ \to e^+\gamma$	e-γ
$\mu^+ \to e^+\gamma\nu\bar{\nu}$	e-γ, 1-γ
$\mu^+ \to e^+\gamma\gamma$	e-γ-γ, e-γ
$\mu^+ \to e^+e^+e^-$	e-e-e
$\mu^+ \to e^+e^+e^-\nu\bar{\nu}$	e-e-e
$\mu^+ \to e^+\nu\bar{\nu}$	1-e
$\mu^+ \to e^+\gamma f$ (f = familon)	e-γ
$\pi^0 \to \gamma\gamma$	γ-γ, 1-γ
$\pi^- p \to n\gamma$	1-γ

- Crystal Box 1988

Analysis for massless familon $m_a \approx 0$
(with 1.4×10^{12} stopped μ^+) yields:

$$\mathrm{BR}(\mu \to e\,a\,\gamma) < 1.1 \times 10^{-9} \quad (90\%\ \mathrm{CL})$$

$$\mathrm{BR}(\mu \to e\,a\,\gamma) \approx \frac{\alpha_{\rm em}}{2\pi}\mathcal{I}(x_{\rm min}, y_{\rm min})\mathrm{BR}(\mu \to e\,a)$$

Hirsch et al. '09

$$\mathcal{I}(x_{\rm min}, y_{\rm min}) = \int_{x_{\rm min}, y_{\rm min}}^{1} \mathrm{d}x\mathrm{d}y \frac{(x-1)(2-xy-y)}{y^2(1-x-y)}$$

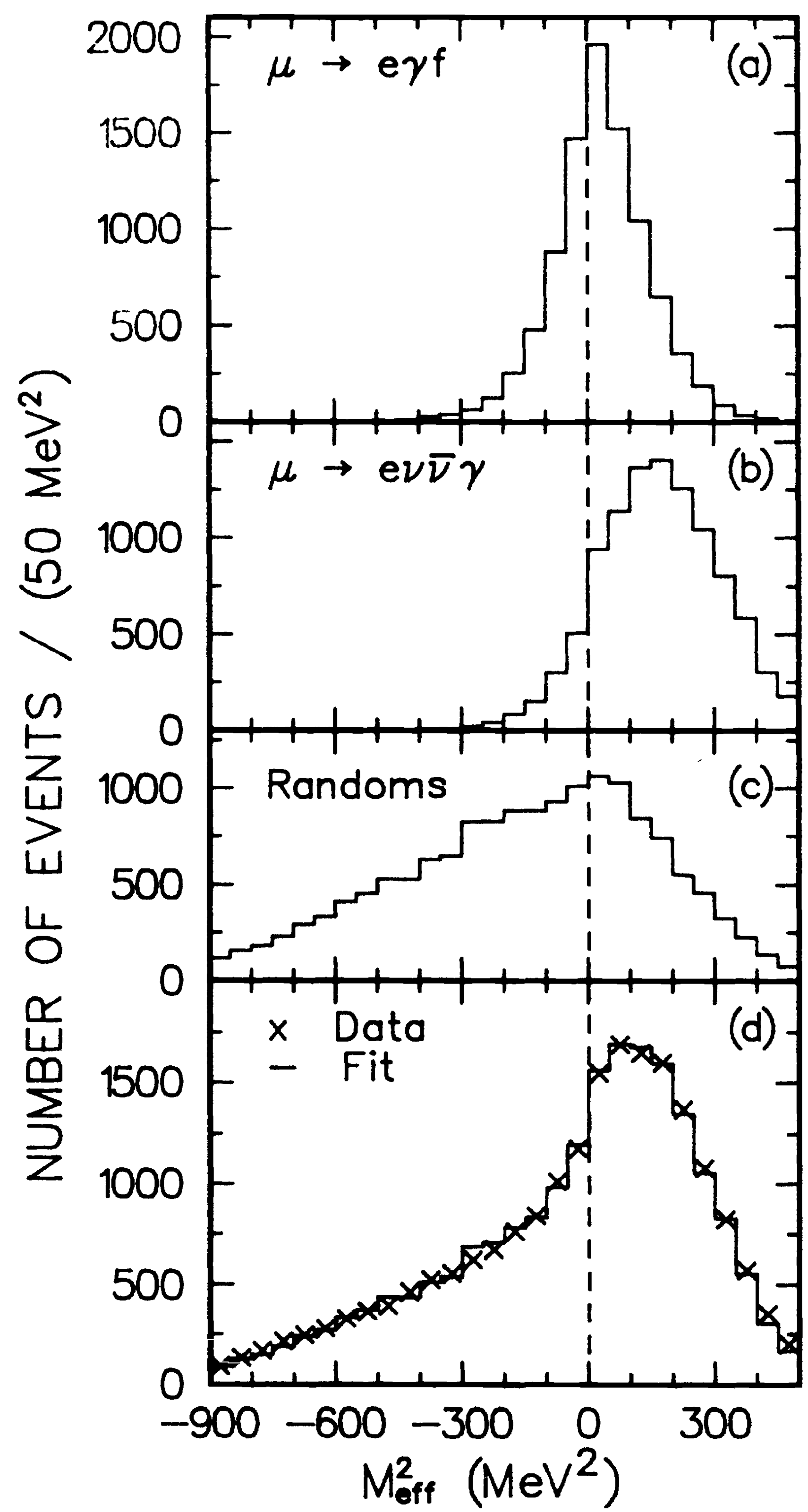
$$x = 2E_e/m_\mu \qquad y = 2E_\gamma/m_\mu$$

Crystal Box energy thresholds:

$$E_e > 38\ \mathrm{MeV}\,, \quad E_\gamma > 38\ \mathrm{MeV} \quad \Rightarrow \quad x_{\rm min} = y_{\rm min} = 0.72$$

$$\Rightarrow \quad F_{e\mu} \; > \; 9.8 \times 10^8\ \mathrm{GeV}$$

Slightly weaker but independent
of V/A nature of the couplings



Past searches: $\tau \to e\, a\,,\, \tau \to \mu\, a$

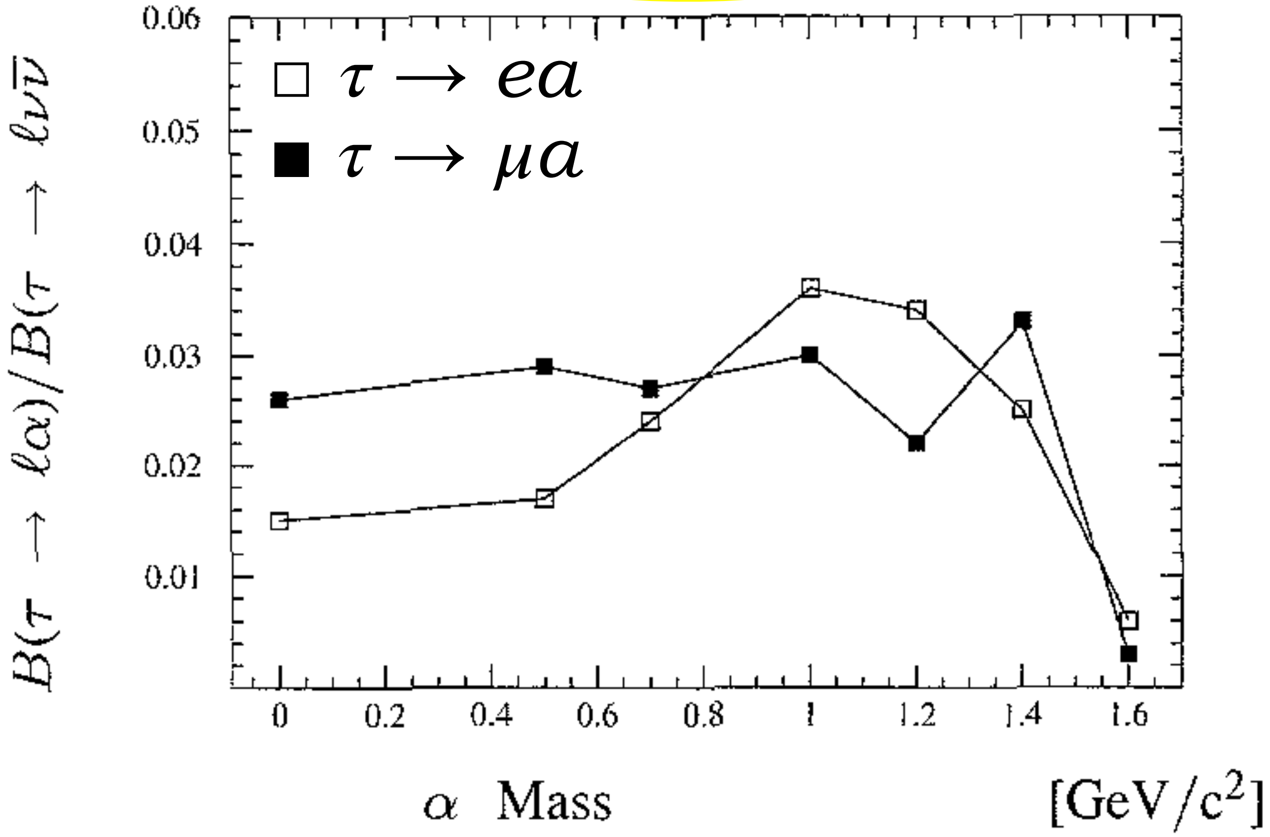
- ARGUS 1995

A search for the lepton-flavour violating decays $\tau \to e\alpha$, $\tau \to \mu\alpha$

Z. Phys. C 68, 25–28 (1995)

ARGUS Collaboration

With 472 pb^{-1}:



$m_a \approx 0$:

$$\mathrm{BR}(\tau \to e\, a) < 2.7 \times 10^{-3} \quad (95\%\ \mathrm{CL}) \quad \Rightarrow \quad F_{\tau e} \gtrsim 4.3 \times 10^{6}\ \mathrm{GeV}\,,$$
$$\mathrm{BR}(\tau \to \mu\, a) < 4.5 \times 10^{-3} \quad (95\%\ \mathrm{CL}) \quad \Rightarrow \quad F_{\tau \mu} \gtrsim 3.3 \times 10^{6}\ \mathrm{GeV}\,.$$

Summary of the model-independent bounds

Bounds on ALP-electron couplings from energy loss in star systems (red giants, white dwarfs) due to processes like:

$$e^- + X \;\to\; e^- + a + X$$

If a lighter than T inside the star $\quad m_a \;<\; \mathcal{O}(10)\ \text{keV} \quad \Rightarrow \quad F^A_{ee} \gtrsim 3.7 \times 10^9\ \text{GeV}$

Bertolami at al '14

Comparison in the case $m_a \approx 0$

Process	Limit on the BR	Decay constant	Lower Bound (95% CL)
Star cooling	–	F^A_{ee}	3.7×10^9 GeV
$\mu \to e\, a$	$< 2.6 \times 10^{-6}$ (90% CL)	$F_{\mu e}$ (V or A)	5.0×10^9 GeV
$\mu \to e\, a$	$< 1.3 \times 10^{-6}$ (90% CL)	$F_{\mu e}$ ($V + A$)	7.0×10^9 GeV
$\mu \to e\, a$	$< 5.8 \times 10^{-5}$ (90% CL)	$F_{\mu e}$ ($V - A$)	1.0×10^9 GeV
$\mu \to e\, a\, \gamma$	$< 1.1 \times 10^{-9}$ (90% CL)	$F_{\mu e}$	8.1×10^8 GeV
$\tau \to e\, a$	$< 2.7 \times 10^{-3}$ (95% CL)	$F_{\tau e}$	4.3×10^6 GeV
$\tau \to \mu\, a$	$< 4.5 \times 10^{-3}$ (95% CL)	$F_{\tau\mu}$	3.3×10^6 GeV

$$F^{V,A}_{ij} \equiv \frac{2 f_a}{C^{V,A}_{ij}} \qquad\qquad F_{ij} \equiv \frac{2 f_a}{\sqrt{|C^V_{ij}|^2 + |C^A_{ij}|^2}}$$

Summary of the model-independent bounds

Bounds on ALP-electron couplings from energy loss in star systems (red giants, white dwarfs) due to processes like:

$$e^- + X \;\to\; e^- + a + X$$

Hints (~3σ) for non-standard WD cooling require: $F^A_{ee} \;\approx\; 6 \times 10^9$ GeV

Giannotti at al '17

Comparison in the case $m_a \approx 0$

Process	Limit on the BR	Decay constant	Lower Bound (95% CL)
Star cooling	–	F^A_{ee}	3.7×10^9 GeV
$\mu \to e\, a$	$< 2.6 \times 10^{-6}$ (90% CL)	$F_{\mu e}$ (V or A)	5.0×10^9 GeV
$\mu \to e\, a$	$< 1.3 \times 10^{-6}$ (90% CL)	$F_{\mu e}$ ($V + A$)	7.0×10^9 GeV
$\mu \to e\, a$	$< 5.8 \times 10^{-5}$ (90% CL)	$F_{\mu e}$ ($V - A$)	1.0×10^9 GeV
$\mu \to e\, a\, \gamma$	$< 1.1 \times 10^{-9}$ (90% CL)	$F_{\mu e}$	8.1×10^8 GeV
$\tau \to e\, a$	$< 2.7 \times 10^{-3}$ (95% CL)	$F_{\tau e}$	4.3×10^6 GeV
$\tau \to \mu\, a$	$< 4.5 \times 10^{-3}$ (95% CL)	$F_{\tau \mu}$	3.3×10^6 GeV

$$F^{V,A}_{ij} \equiv \frac{2 f_a}{C^{V,A}_{ij}} \qquad\qquad F_{ij} \equiv \frac{2 f_a}{\sqrt{|C^V_{ij}|^2 + |C^A_{ij}|^2}}$$

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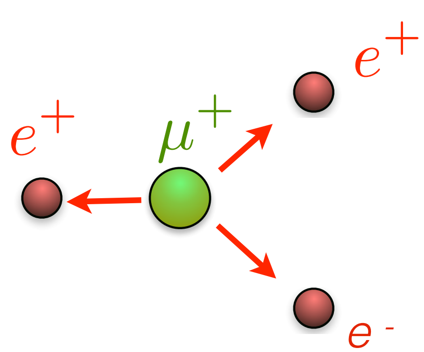
- Prospects at upcoming LFV exps? Can we test ALPs with LFV *beyond stars*?
- Only within specific models we can relate F_{ee}, $F_{\mu e}$, etc.

Mu3e: The $\mu^+ \to e^+e^+e^-$ search

slide borrowed from A. Papa

- The Mu3e experiment aims to search for $\mu^+ \to e^+ e^+ e^-$ with a sensitivity of $\sim 10^{-15}$ (Phase I) up to down $\sim 10^{-16}$ (Phase II). Previous upper limit $BR(\mu^+ \to e^+ e^+ e^-) \leq 1 \times 10^{-12}$ @90 C.L. by SINDRUM experiment)
- Observables (E_e, t_e, vertex) to characterize $\mu \to eee$ events

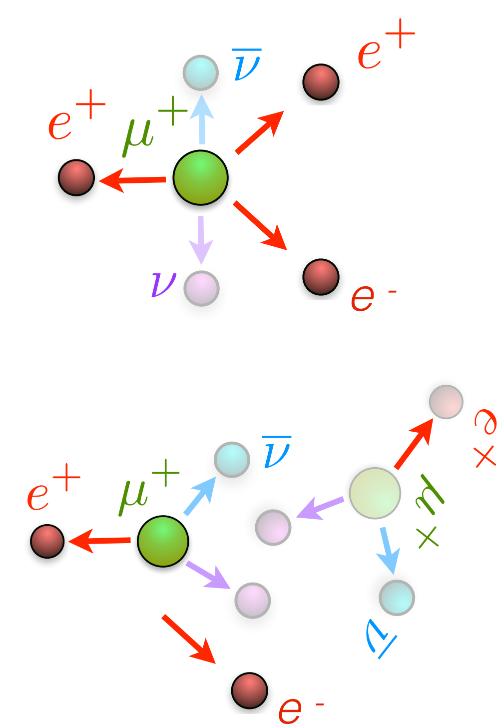
Signature

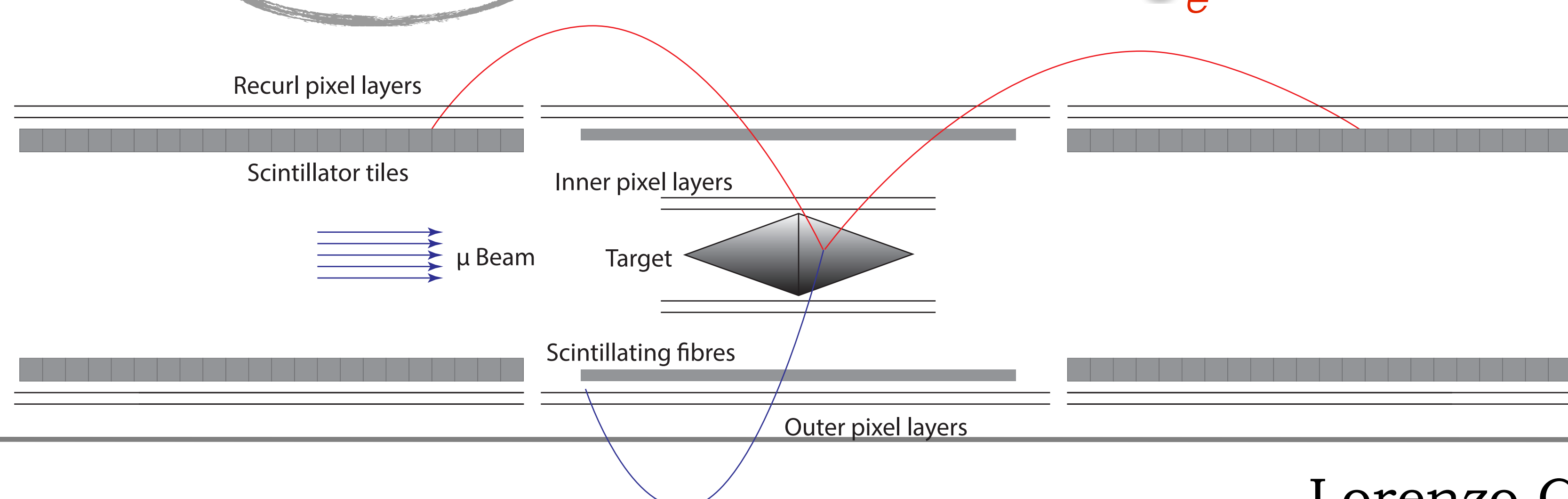


$$\Delta t_{eee} = 0 \qquad \Sigma \overline{p}_e = 0$$

$$\Sigma E_e = m_\mu$$

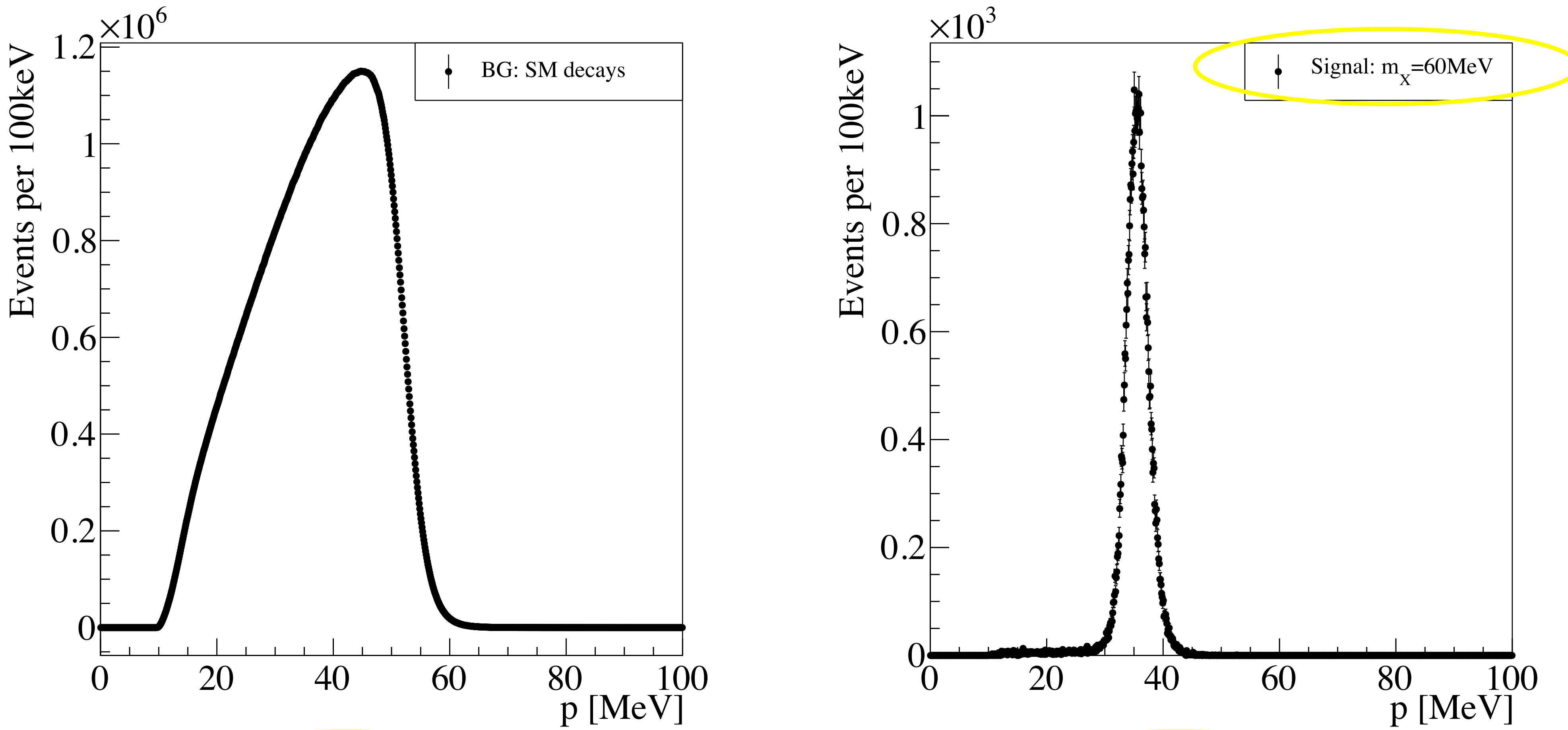
Background





- Mu3e prospect for $\mu \to e\, a$ (Perrevoort '18)

Potential search for performed on momentum histograms
filled with online reconstructed short tracks



(a) Simulated background events.

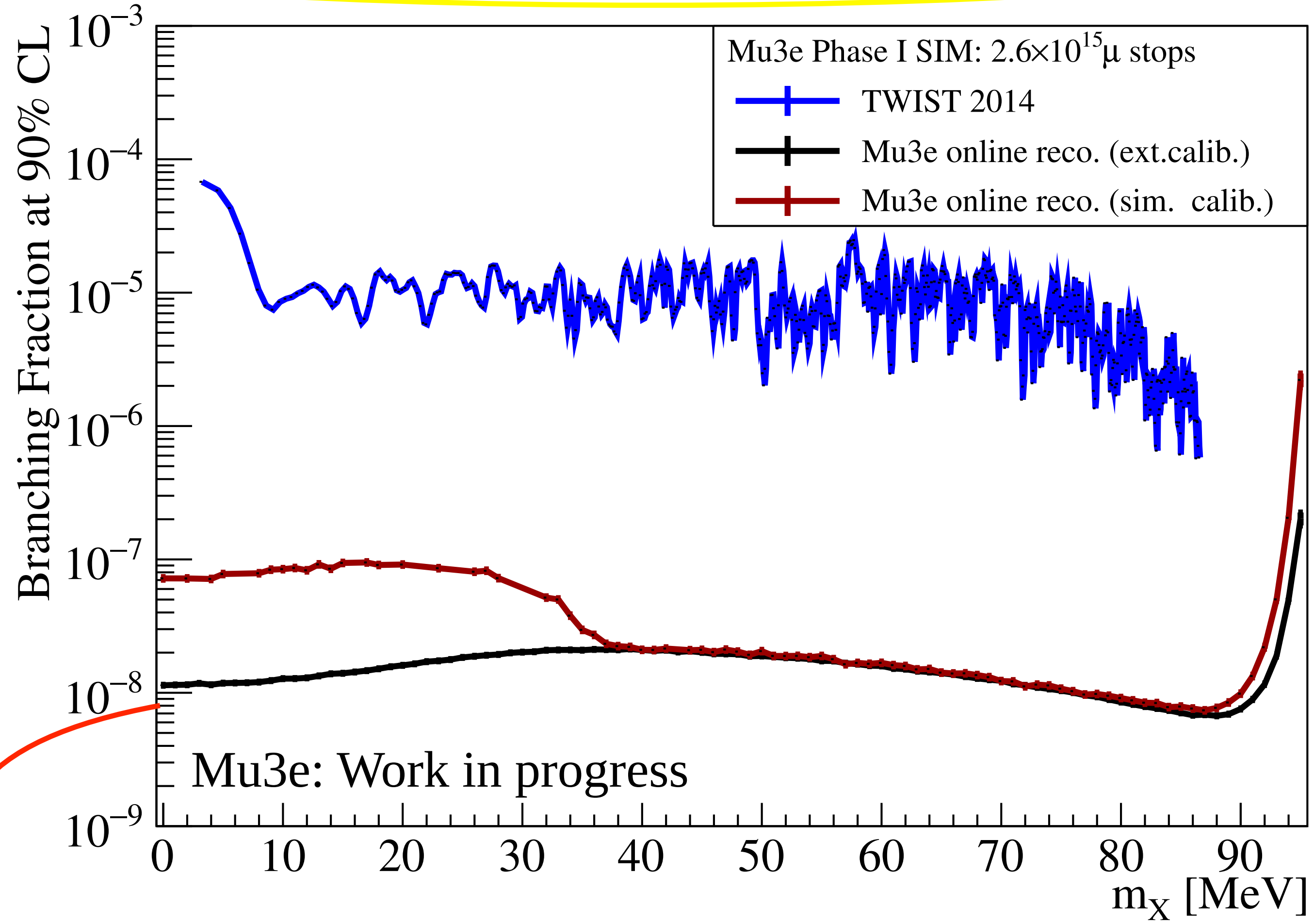
(b) Simulated $\mu \to eX$ signal events.

Perrevoort (Mu3e) '18

- Mu3e prospect for $\mu \to e\, a$ (Perrevoort '18)

Potential search for performed on momentum histograms filled with online reconstructed short tracks

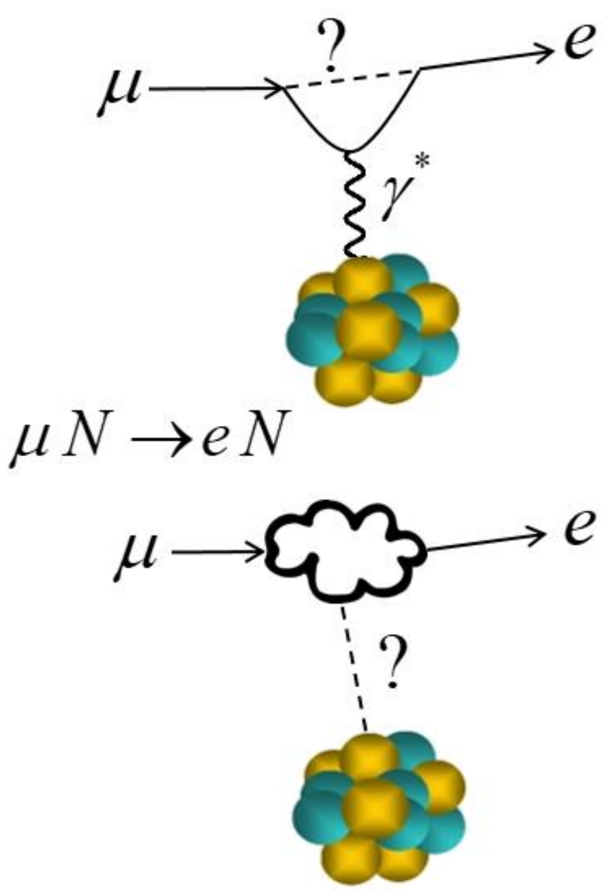
Expected limit for phase I ($2.6 \times 10^{15}\ \mu^+$):

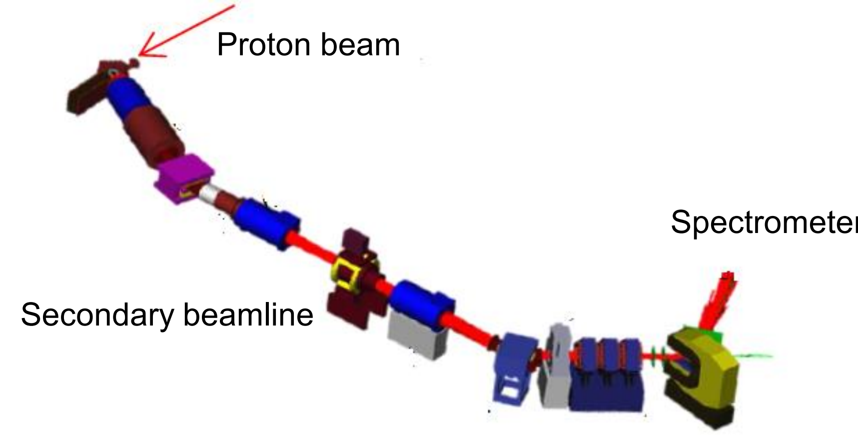


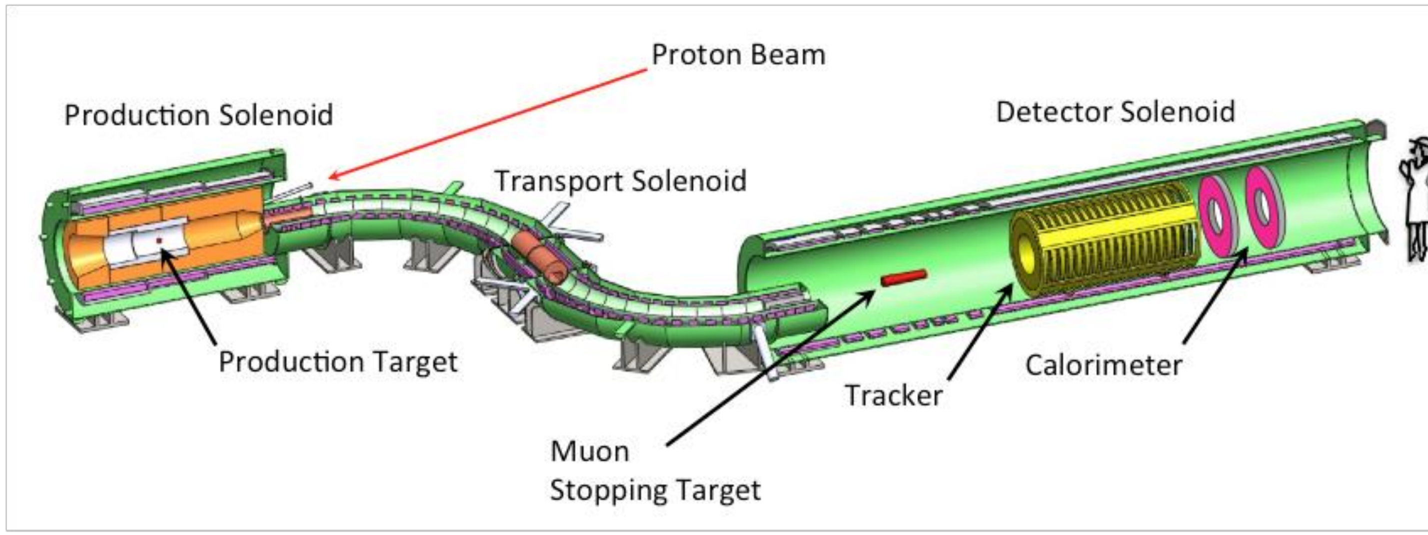
Perrevoort (Mu3e) '18

$$m_a \approx 0: \quad \mathrm{BR}(\mu \to e\, a) < 10^{-8} \quad \Longrightarrow \quad F_{\mu e} \gtrsim 9 \times 10^{10}\ \mathrm{GeV}.$$

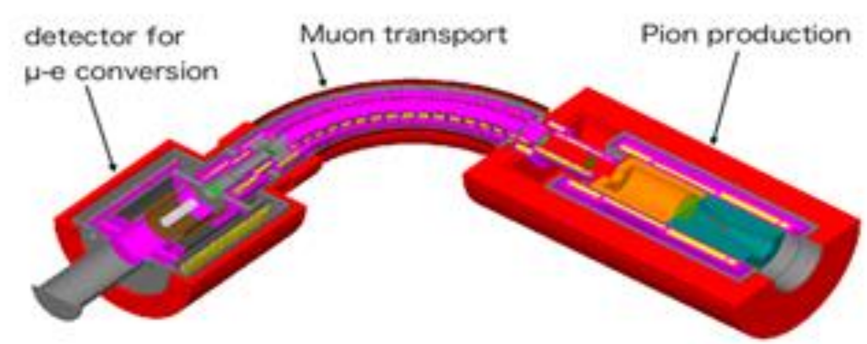
$\mu \to e$ conversion in nuclei experiments





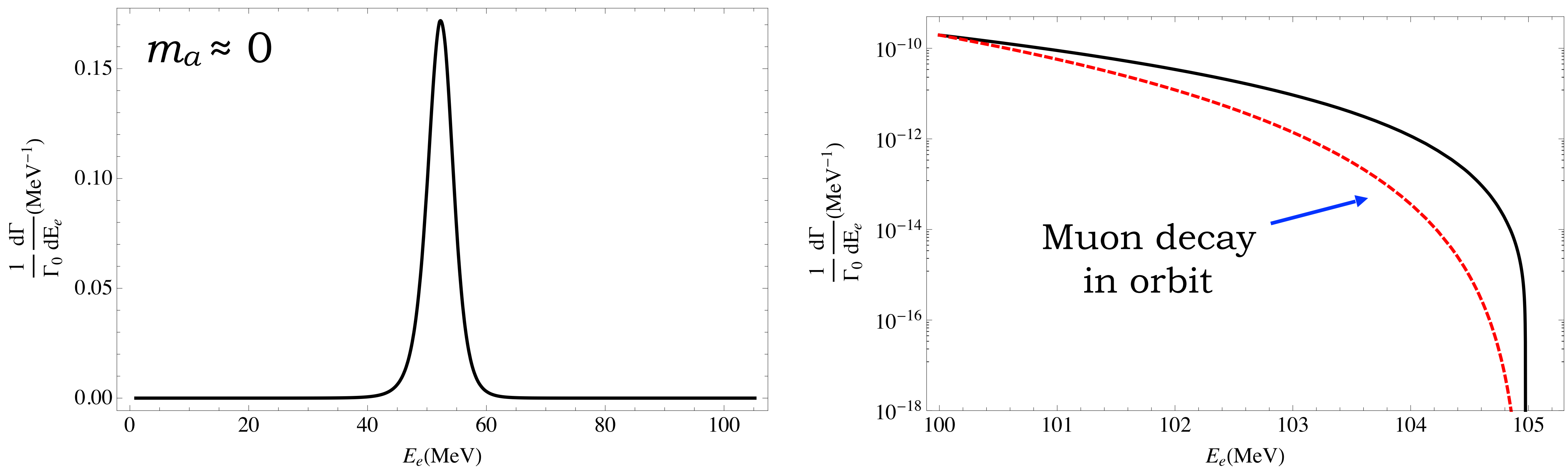


David Hitlin
Beijing CLFV School
June 3-7, 2019
Lecture 1



- Prospect at $\mu \to e$ conversion experiments (Garcia i Tomo et al. '11)

Spectrum of $\mu \to ea$ emission in orbit (for Al):



Sensitivity in terms of the $\mu \to e$ conv. limit:

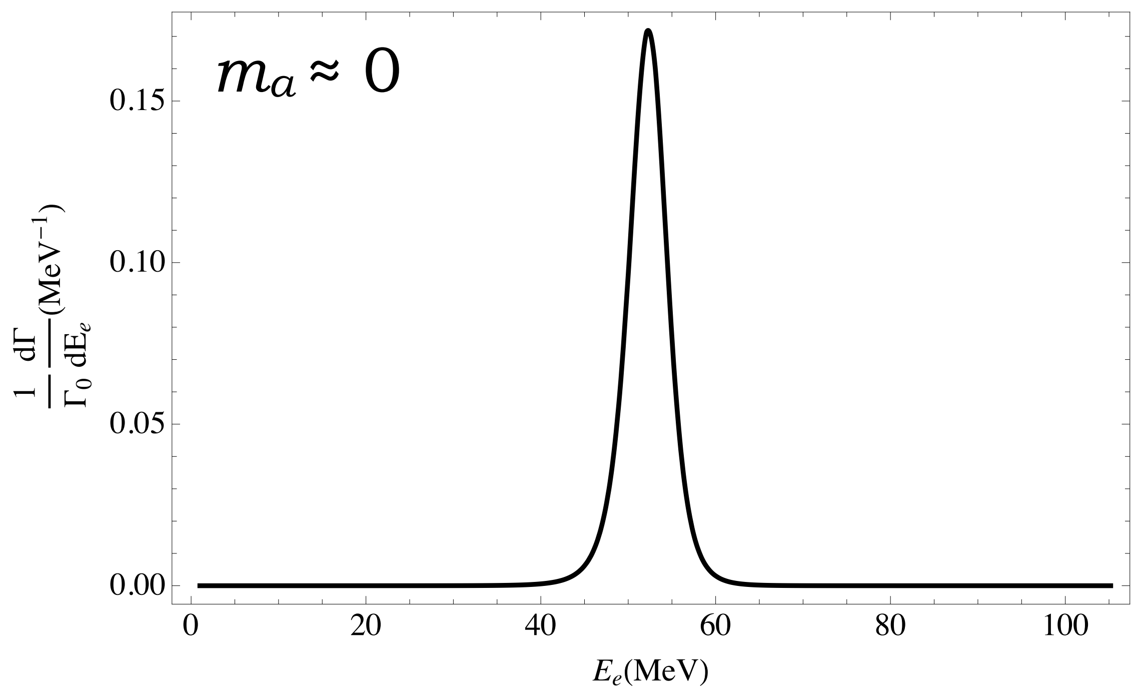
Phase-space correction factor

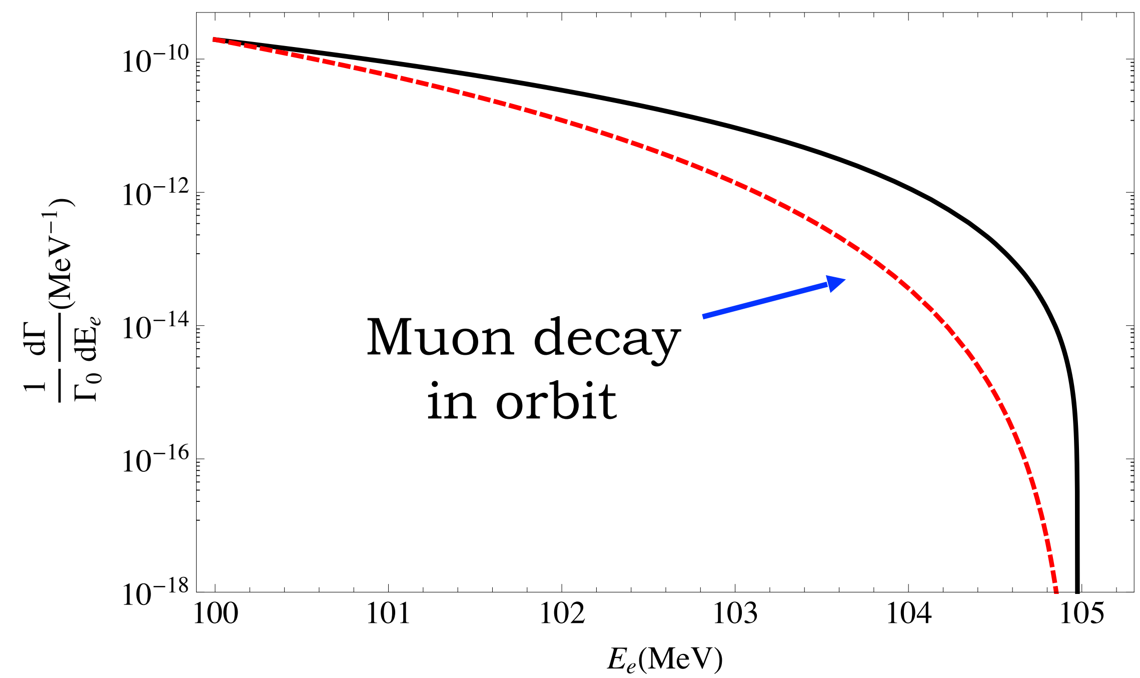
$$B(\mu \to eJ) \sim \frac{N_R R_{\mu e}}{f_J} \frac{\Gamma_{\text{capture}}}{\Gamma(\mu \to e\nu_\mu \bar{\nu}_e)} \sim \frac{N_R R_{\mu e}}{f_J} 1.5$$

Fraction of $\mu \to ea$ events in the signal region

- Prospect at $\mu \to e$ conversion experiments (Garcia i Tomo et al. '11)

Spectrum of $\mu \to ea$ emission in orbit (for Al):





Sensitivity in terms of the $\mu \to e$ conv. limit:

$$B(\mu \to eJ) \sim \frac{N_R R_{\mu e}}{f_J} \frac{\Gamma_{\text{capture}}}{\Gamma(\mu \to e\nu_\mu \bar{\nu}_e)} \sim \frac{N_R R_{\mu e}}{f_J} 1.5 \Rightarrow 2\times10^{-6}$$

Phase-space correction factor (N_R)

27 (in Al)

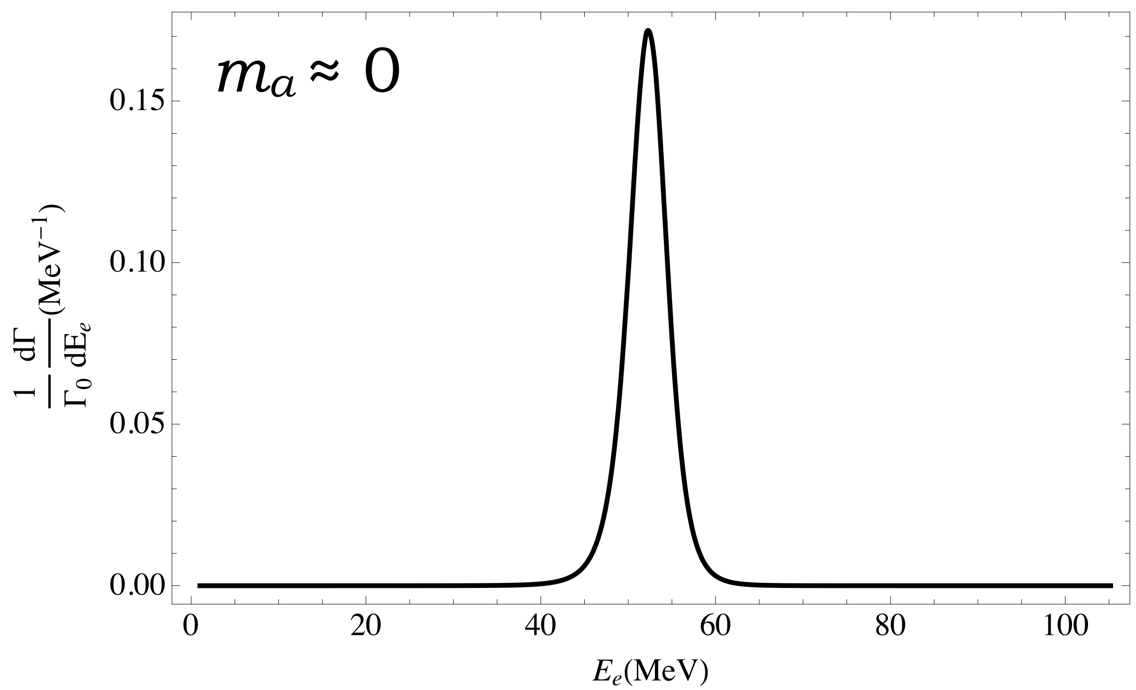
10^{-17} ($R_{\mu e}$)

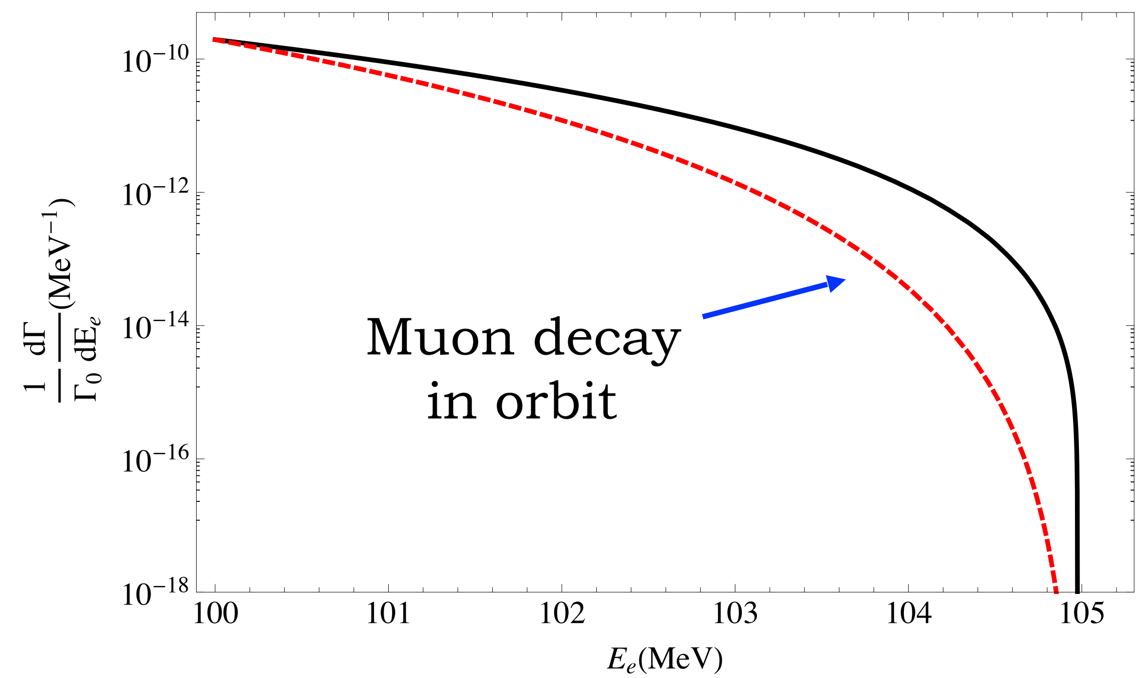
Fraction of $\mu \to ea$ events in the signal region (f_J)

2×10^{-10} (E_e > 100 MeV)

- Prospect at $\mu \to e$ conversion experiments (Garcia i Tomo et al. '11)

Spectrum of $\mu \to ea$ emission in orbit (for Al):





Sensitivity in terms of the $\mu \to e$ conv. limit:

$$B(\mu \to eJ) \sim \frac{N_R R_{\mu e}}{f_J} \frac{\Gamma_{\text{capture}}}{\Gamma(\mu \to e \nu_\mu \bar{\nu}_e)} \sim \frac{N_R R_{\mu e}}{f_J} 1.5 \Rightarrow 2\times10^{-6}$$

Possible bound at the level of Jodidio et al.

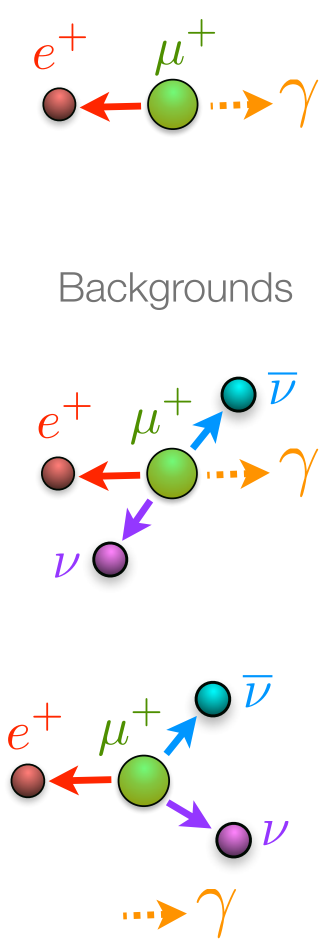
Limited by the $\mu \to e$ conv. signal region (only the tail included): dedicated search?

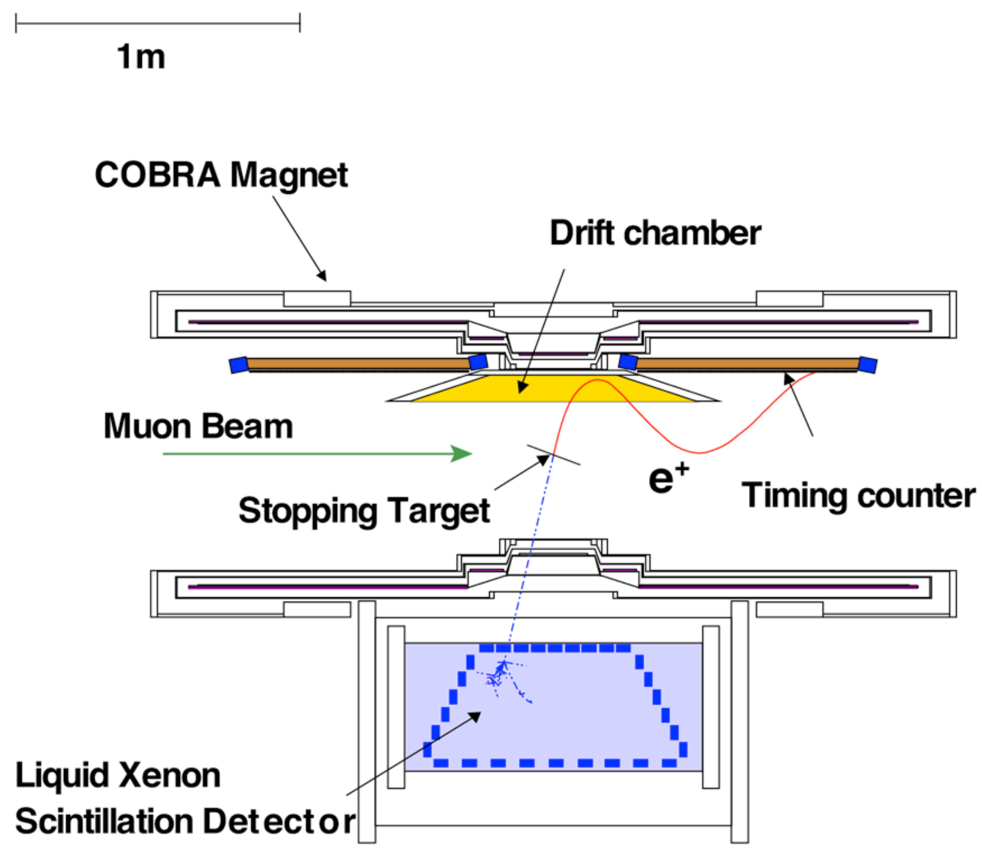
A. Baldini et al. (MEG Collaboration), Eur. Phys. J. C73 (2013) 2365

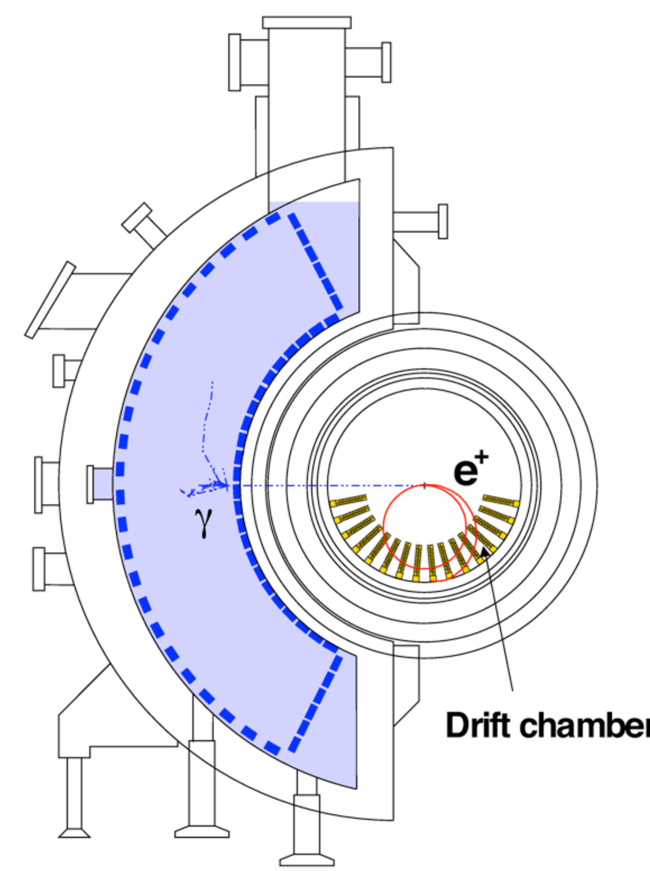
MEG: Signature and experimental setup

- The MEG experiment aims to search for $\mu^+ \to e^+ \gamma$ with a sensitivity of ~10^{-13} (previous upper limit $BR(\mu^+ \to e^+ \gamma) \leq 1.2 \times 10^{-11}$ @90 C.L. by MEGA experiment)
- Five observables (E_g, E_e, t_{eg}, ϑ_{eg}, ϕ_{eg}) to characterize $\mu \to e\gamma$ events

Signature







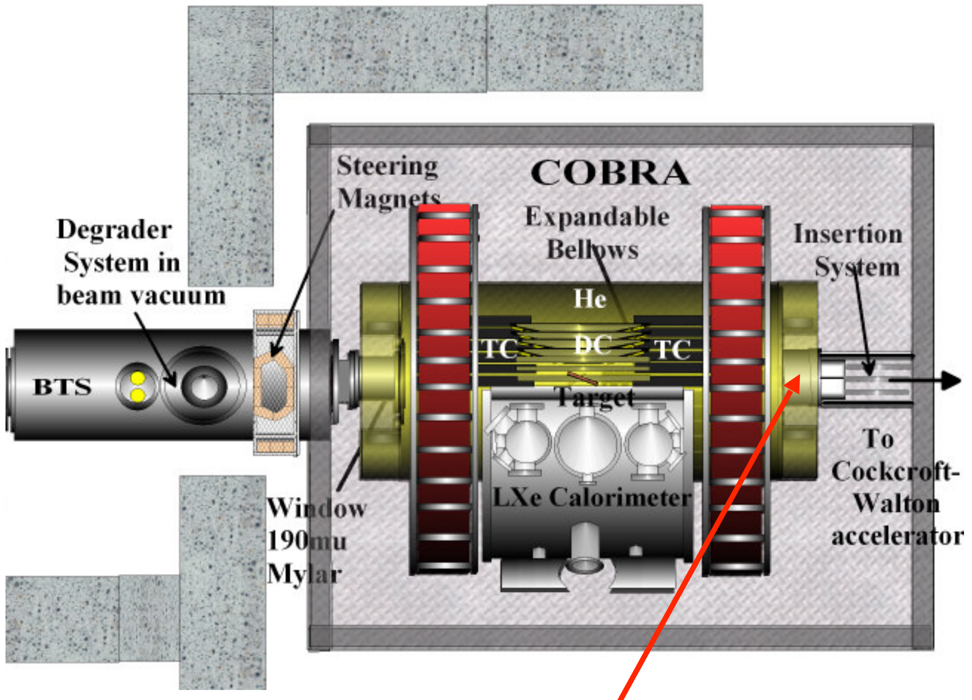
slide borrowed from A. Papa

Future prospects: MEG II

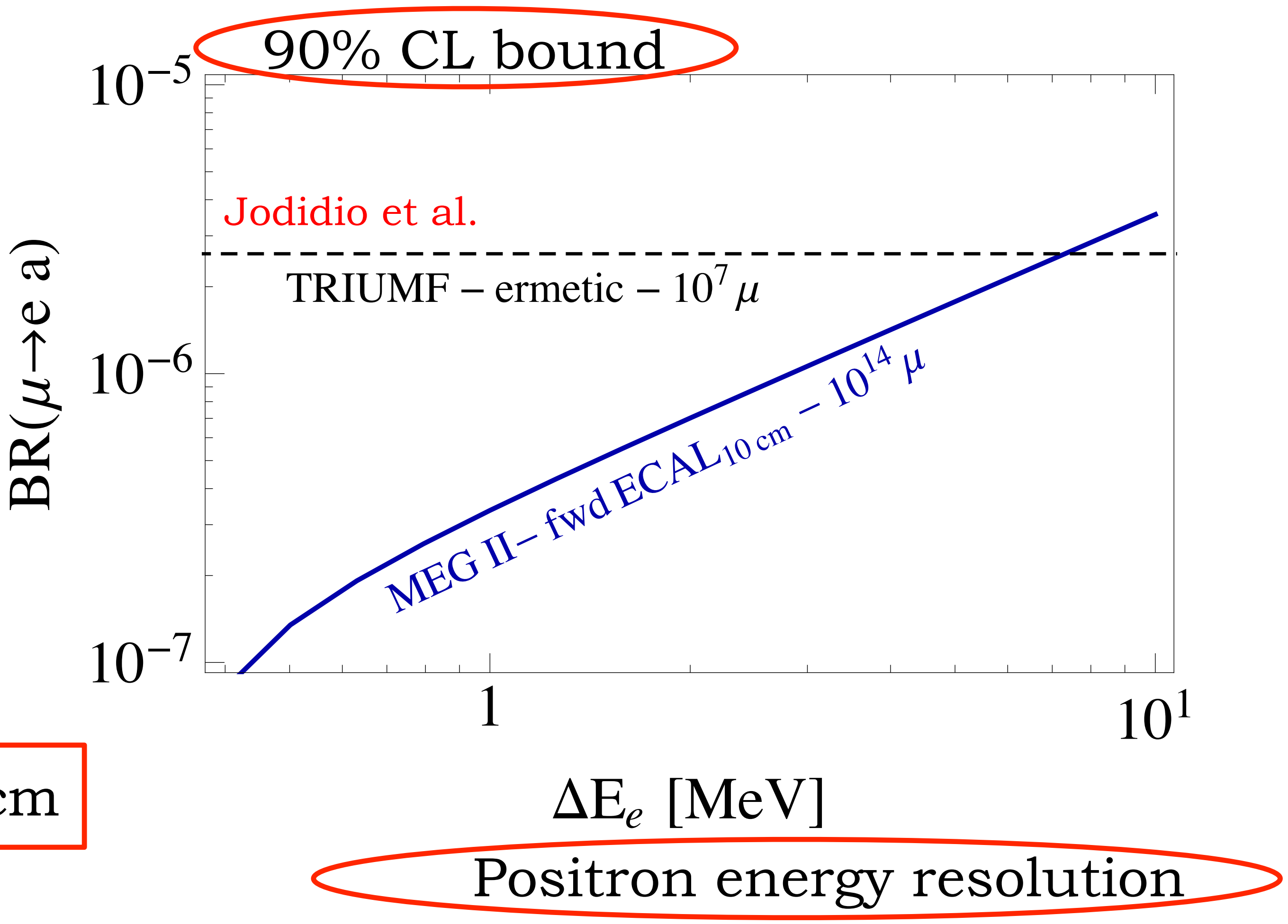
- Prospect at MEG II

What about a Jodidio-like search at MEG II for $m_a \approx 0$ with a forward calorimeter?

Poor theorists' estimate of the sensitivity of a dedicate run
(2 weeks dedicated run with $10^8\ \mu^+/s$):



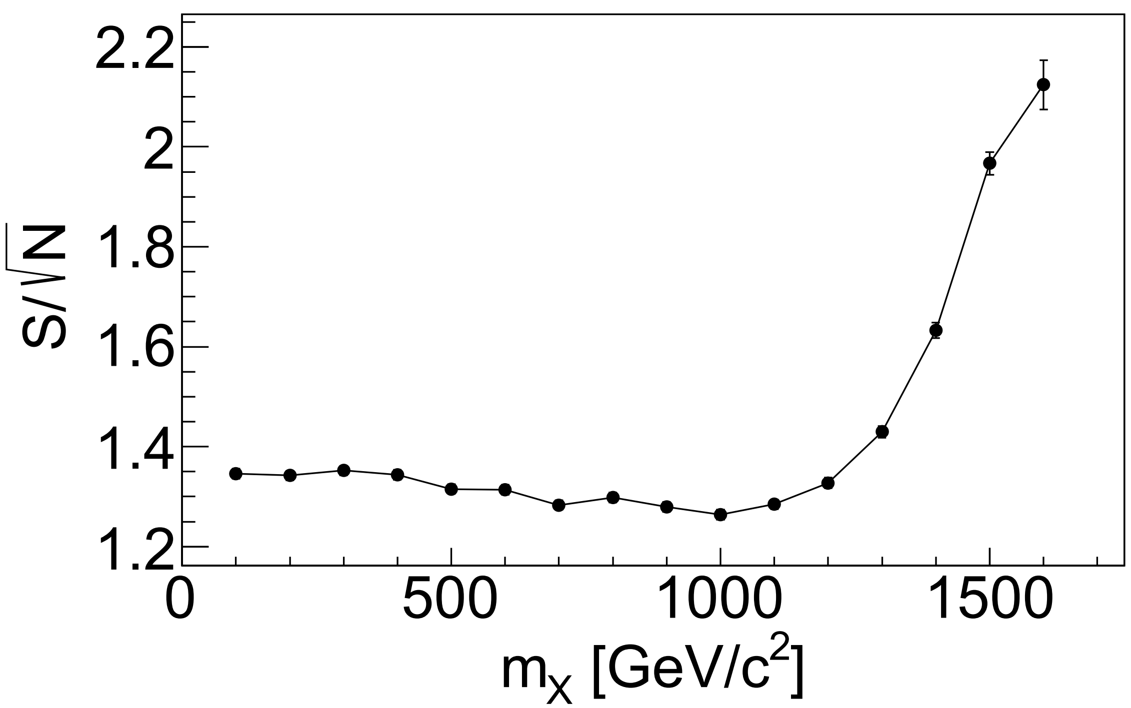
~1.5 m from the target, radius ~ 10 cm

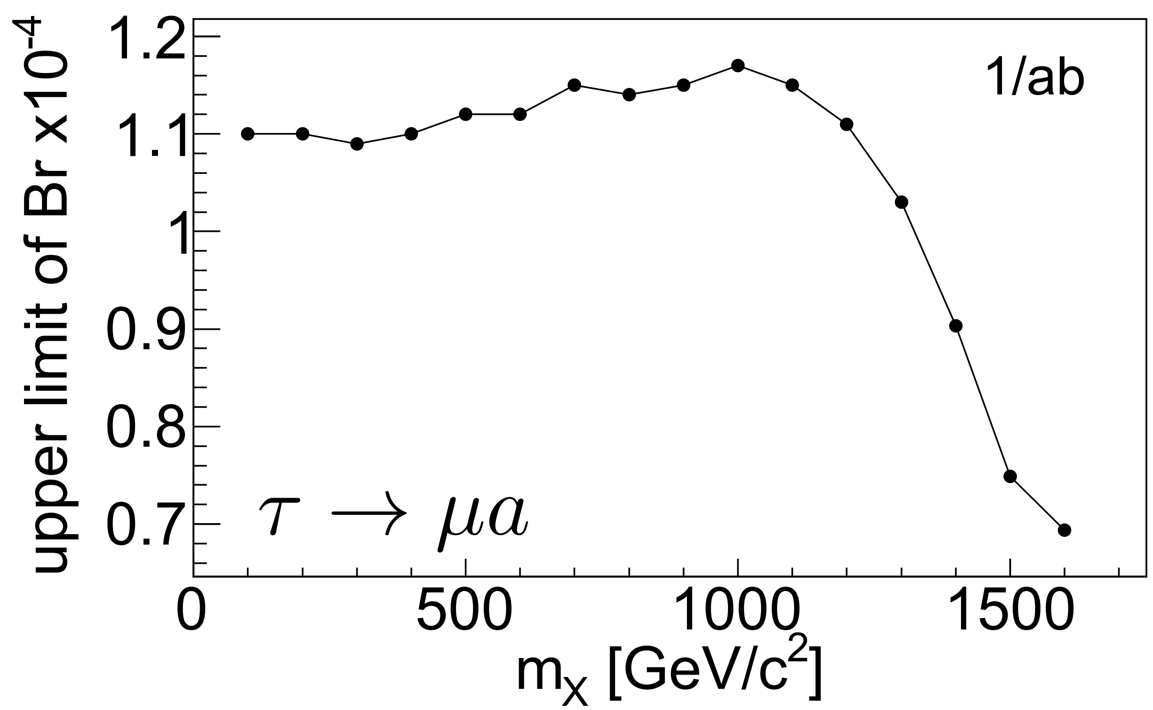


$$\Delta E_e = 1\,\mathrm{MeV}: \quad \mathrm{BR}(\mu \to ea) < 3 \times 10^{-7} \quad (10^{14}\,\mu^+)$$

- Belle prospect for $\tau \to \mu\, a$ (Yoshinobu Hayasaka '17)

Simulation of S and B and limit that can be set using the Belle data set (1/ab):





Yoshinobu Hayasaka (Belle) '17

$m_a \approx 0$:

Belle (1/ab) prospect: $\mathrm{BR}(\tau \to \mu\, a) < 1.1 \times 10^{-4} \quad \Rightarrow \quad F_{\tau\mu} \gtrsim 2.1 \times 10^{7}$ GeV

Belle-II (50/ab) prospect: $\mathrm{BR}(\tau \to \mu\, a) < 1.4 \times 10^{-5} \quad \Rightarrow \quad F_{\tau\mu} \gtrsim 5.9 \times 10^{7}$ GeV

Estimated by rescaling as $\sqrt{\mathcal{L}}$

LFV decays into a leptonic familon

$\mu \to ea$ differential decay rate:

$$\frac{\mathrm{d}\Gamma(\mu^+ \to e^+\, a)}{\mathrm{d}\cos\theta} = \frac{\Gamma_{\mu\to e\, a}}{2}\left[1 + 2P\cos\theta\,\frac{C^V_{e\mu}C^A_{e\mu}}{(C^V_{e\mu})^2 + (C^A_{e\mu})^2}\right]$$

Anisotropy (thus exp. bound) depends on the model:

$$C_{V/A} = V_R^\dagger X_R V_R \pm V_L^\dagger X_L V_L$$

Anarchical model

RH rotations dominate:

$$C_V^{ij} \approx C_A^{ij}$$

Stronger exp. limit applies:

$$\mathrm{BR}(\mu \to ea) < 2.6 \times 10^{-6}$$

But suppressed rate:

$$\Gamma(\mu \to ea) \approx \frac{1}{16\pi}\frac{m_\mu^3}{f^2}|(V_R)_{12}|^2$$

$(V_R)_{12} \to \mathcal{O}(m_e/m_\mu)$

Hierarchical model

LH rotations dominate:

$$C_V^{ij} \approx -C_A^{ij}$$

Weaker exp. limit applies:

$$\mathrm{BR}(\mu \to ea) < 5.8 \times 10^{-5}$$

But larger rate:

$$\Gamma(\mu \to ea) \approx \frac{1}{16\pi}\frac{m_\mu^3}{f^2}|(V_L)_{12}|^2$$

$(V_L)_{12} \to \mathcal{O}(\epsilon)$

Present bounds

$m_a \approx 0$	Anarchical model	Hierarchical model
$\mu \to e\, a$	$f > 2 \times 10^7$ GeV	5×10^8 GeV
$\mu \to e\, a\, \gamma$	10^7 GeV	4×10^8 GeV
$\tau \to e\, a$	5×10^3 GeV	10^6 GeV
$\tau \to \mu\, a$	4×10^5 GeV	10^6 GeV

To be compared to the bound (from the coupling to electrons) from star cooling:

$$f > 2 \times 10^{10}\ \text{GeV}$$

$m_a \ < \ \mathcal{O}(10)$ keV

Bounds on the flavour-breaking scale f

Future sensitivities

$m_a \approx 0$	Anarchical model		Hierarchical model
$\mu \to e\, a$	$f > 8 \times 10^8$ GeV	Mu3e phase I	4×10^{10} GeV
$\mu \to e\, a\, \gamma$	?		?
$\tau \to e\, a$			
$\tau \to \mu\, a$	7×10^6 GeV	Belle2 (50/ab)	2×10^7 GeV

To be compared to the bound (from the coupling to electrons) from star cooling:

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… and hints for non-standard energy loss in star systems that could be fitted in this model with:

$$f \approx 3 \times 10^{10}\,\text{GeV} \qquad m_a < \mathcal{O}(10)\ \text{keV}$$

Bounds on the flavour-breaking scale f

Future sensitivities

$m_a \approx 0$	Anarchical model		Hierarchical model
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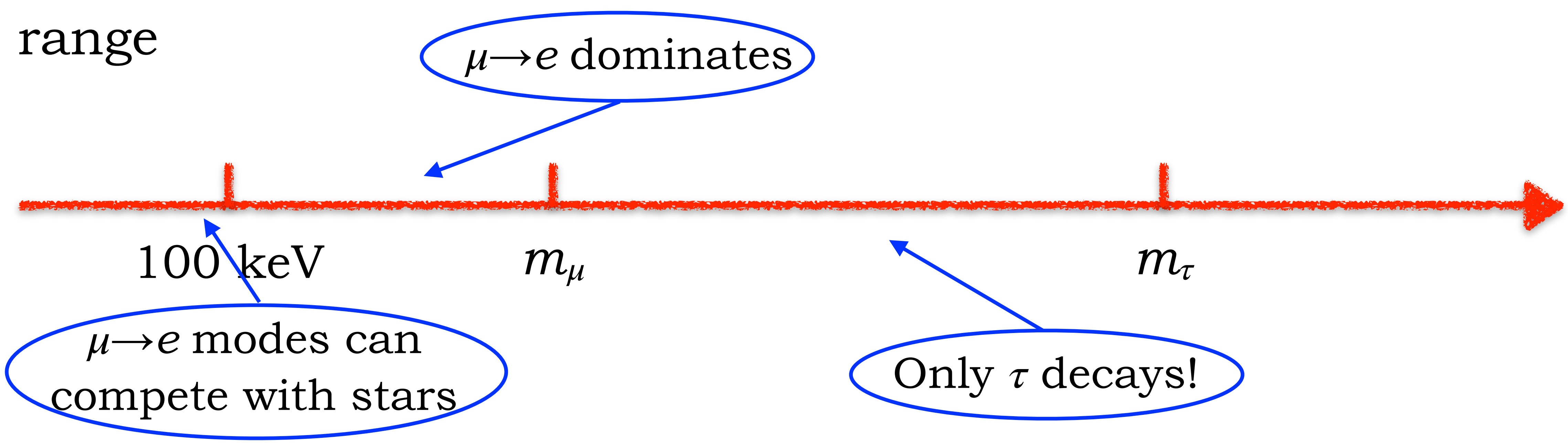
m_a range



Conclusions

In general, PNGBs from non-universal global U(1) give rise to lepton-flavour-violating decays

We have huge room for improvement over the old limits

Essential interplay among μ, τ, and astrophysical bounds

Very large symmetry-breaking scales can be probed

Future CLFV limits (e.g. on a leptonic familon) can supersede stellar bounds even in the small mass range

Grazie!

谢谢!

Additional slides

The axiflavon setup

LC Goertz Redigolo Ziegler Zupan ‘16

The axion identified with the Nambu-Goldstone boson of a broken global FN U(1), *i.e.* as the phase of the flavon field → “axiflavon”

$$\Phi = \frac{1}{\sqrt{2}}(V_\Phi + \phi)e^{ia/V_\Phi}$$

Couplings gluons and photons via colour and electromagnetic anomalies:

$$\mathcal{L} = \frac{\alpha_s}{8\pi}\frac{a}{f_a}G\tilde{G} + \frac{E}{N}\frac{\alpha_{\rm em}}{8\pi}\frac{a}{f_a}F\tilde{F} \qquad f_a = V_\Phi/2N$$

Anomaly coefficients given by FN charges:

QCD $$N = \frac{1}{2}\sum_i 2[q]_i + [u]_i + [d]_i\,,$$

E.M. $$E = \sum_i \frac{4}{3}\left([q]_i + [u]_i\right) + \frac{1}{3}\left([q]_i + [d]_i\right) + [l]_i + [e]_i\,,$$

[no contributions from messengers, vectorilike under U(1)]

Usual axion mass induced by the QCD anomaly:

$$m_a = 5.7\,\mu{\rm eV}\left(\frac{10^{12}{\rm GeV}}{f_a}\right)$$

The axiflavon setup

$$\mathcal{L} = \frac{\alpha_s}{8\pi}\frac{a}{f_a}G\tilde{G} + \frac{E}{N}\frac{\alpha_{\rm em}}{8\pi}\frac{a}{f_a}F\tilde{F} \qquad f_a = V_\Phi/2N$$

Key observation: FN U(1) to reproduce observed Yukawas is necessarily anomalous and the coefficients are linked to the quark masses:

$$\det m_u \det m_d = \alpha_{ud}\, v^6 \epsilon^{2N},$$

$$\det m_d / \det m_e = \alpha_{de}\, \epsilon^{\frac{8}{3}N-E},$$

$$\alpha_{ud} = \det a_u \det a_d, \;\; \alpha_{de} = \det a_d / \det a_e$$

Ibanez Ross '94, Bineutry Lavignac Ramond '94 '96

$$\frac{E}{N} = \frac{8}{3} - 2\frac{\log\frac{\det m_d}{\det m_e} - \log\alpha_{de}}{\log\frac{\det m_u \det m_d}{v^6} - \log\alpha_{ud}}$$

≈ -0.4 $\qquad \mathcal{O}(1)$

≈ -44 $\qquad \mathcal{O}(1)$

Sharp prediction for the coupling to photons $\frac{1}{4}g_{a\gamma\gamma}aF\tilde{F}$, independent of U(1) charges and little sensitive to O(1)s:

$$\frac{E}{N} \in [2.4, 3.0] \quad \Longrightarrow \quad g_{a\gamma\gamma} \in \frac{[1.0, 2.2]}{10^{16}\text{GeV}}\frac{m_a}{\mu\text{eV}}$$

Compare to DFSZ and KSVZ axions:

$|E/N| \in [0.3, 2.7]$ $\qquad$ $|E/N| \in [0, 6]$

$$m_a = 5.7\,\mu\text{eV}\left(\frac{10^{12}\text{GeV}}{f_a}\right)$$

The axiflavon setup

The axion identified with the Nambu-Goldstone boson of a broken global FN U(1), *i.e.* as the phase of the flavon field → "axiflavon"

$$\Phi = \frac{1}{\sqrt{2}}(V_\Phi + \phi)e^{ia/V_\Phi}$$

SM fermions-axiflavon couplings proportional to the Yukawas but not aligned:

$$y^f_{ij} = a^f_{ij}\left(\frac{\langle\Phi\rangle}{M}\right)^{[f_L]_i+[f_R]_j} \implies \mathcal{L}_{aff} = \lambda^f_{ij} a \bar{f}_{Li} f_{Rj} + \text{h.c.} \qquad \lambda^f_{ij} = i([f_L]_i + [f_R]_j)\frac{v}{V_\Phi} y^f_{ij}$$

flavour violating!

Or in the usual derivative form:

$$\mathcal{L}_{aff} = \frac{\partial^\mu a}{V_\Phi}\left(C^f_{V\,ij}\,\bar{f}_i\gamma_\mu f_j + C^f_{A\,ij}\,\bar{f}_i\gamma_\mu\gamma_5 f_j\right)$$

$$C^f_{V/A} = V^{f\dagger}_R X^f_R V^f_R \pm V^{f\dagger}_L X^f_L V^f_L$$

non-universal charges → non-vanishing off-diagonal couplings

$$V^{f\dagger}_L Y^f V^f_R = Y^f_{diag} \qquad X^f_{R/L} = \begin{pmatrix} [f_{R/L}]_1 & & \\ & [f_{R/L}]_2 & \\ & & [f_{R/L}]_3 \end{pmatrix}$$

Axiflavon phenomenology

Stellar evolution bounds $f_a > 10^8$ GeV [natural DM window 10^{10} GeV < f_a < 10^{13} GeV]

⇨ flavour processes mediated by the dynamical flavon very suppressed

Despite the tiny couplings low-energy searches for rare processes are sensitive to flavour-violating decays to ultralight axiflavons! *E.g.*:

$$K^+ \to \pi^+ a \qquad B^+ \to K^+ a \qquad \mu^+ \to e^+ a$$

Small rates but strong constraints! Most stringent from Kaons:

$$\Gamma(K^+ \to \pi^+ a) \simeq \frac{m_K}{64\pi} |\lambda^d_{21} + \lambda^{d*}_{12}|^2 B_s^2 \left(1 - \frac{m_\pi^2}{m_K^2}\right)$$

$$|\lambda^d_{21} + \lambda^{d*}_{12}| \approx \frac{\sqrt{m_s m_d}}{f_a} \frac{\kappa_{sd}}{N}$$

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$$K^+ \to \pi^+ a \qquad B^+ \to K^+ a \qquad \mu^+ \to e^+ a$$

Small rates but strong constraints! Most stringent from Kaons:

$$\mathrm{BR}(K^+ \to \pi^+ a) \simeq 1.2 \cdot 10^{-10} \left(\frac{m_a}{0.1\,\mathrm{meV}}\right)^2 \left(\frac{\kappa_{sd}}{N}\right)^2$$

$\kappa_{sd}/N \sim \mathcal{O}(1)$

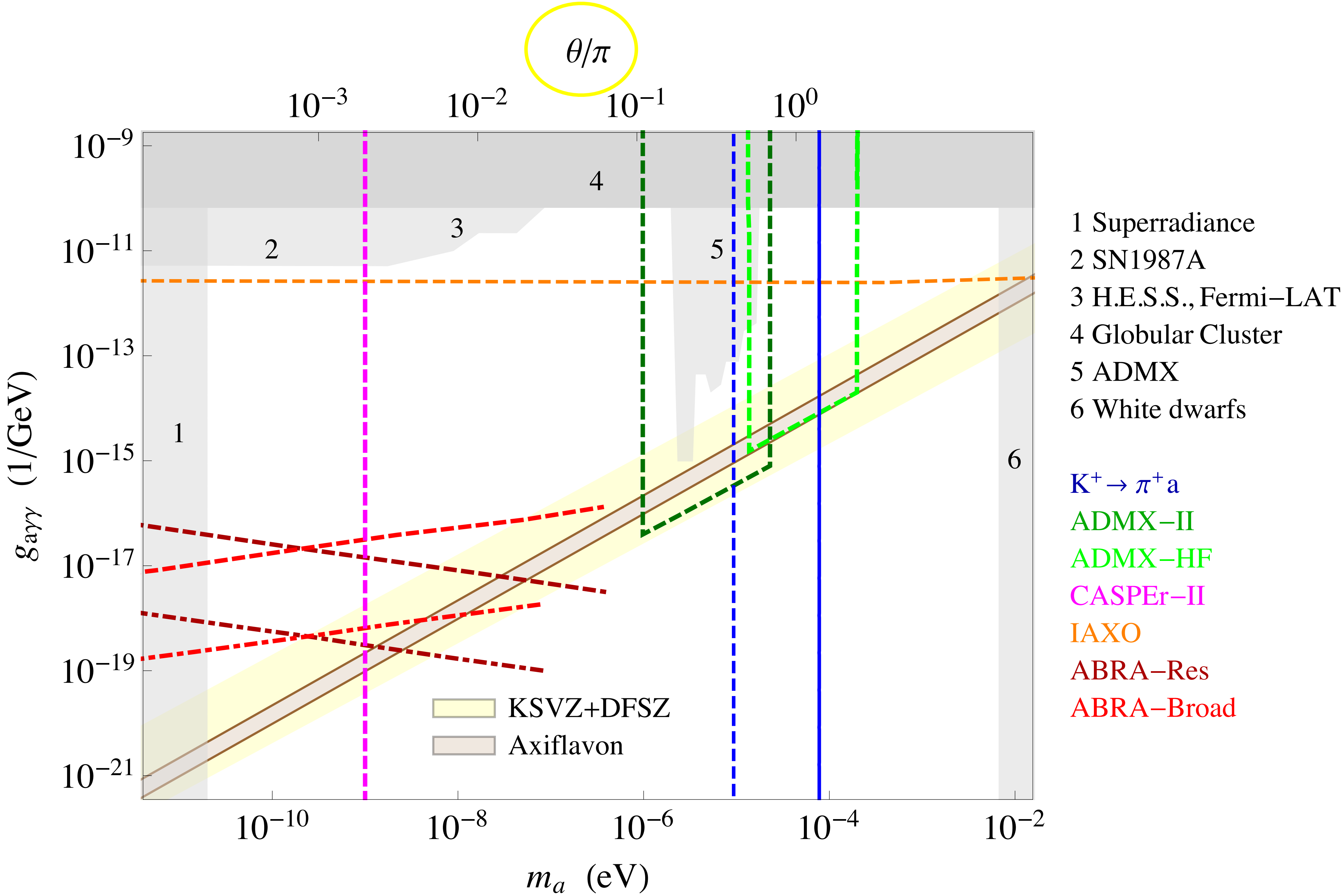
$\mathrm{BR}(K^+ \to \pi^+ a) < 7.3 \cdot 10^{-11}$ ⇨ $f_a \gtrsim \frac{\kappa_{sd}}{N} \times 7.5 \cdot 10^{10}\,\mathrm{GeV}$

E787, E949

Increased sensitivity ~70x is expected at NA62!

Axiflavon phenomenology

Axiflavon can be complementary tested at axion and flavour experiments!



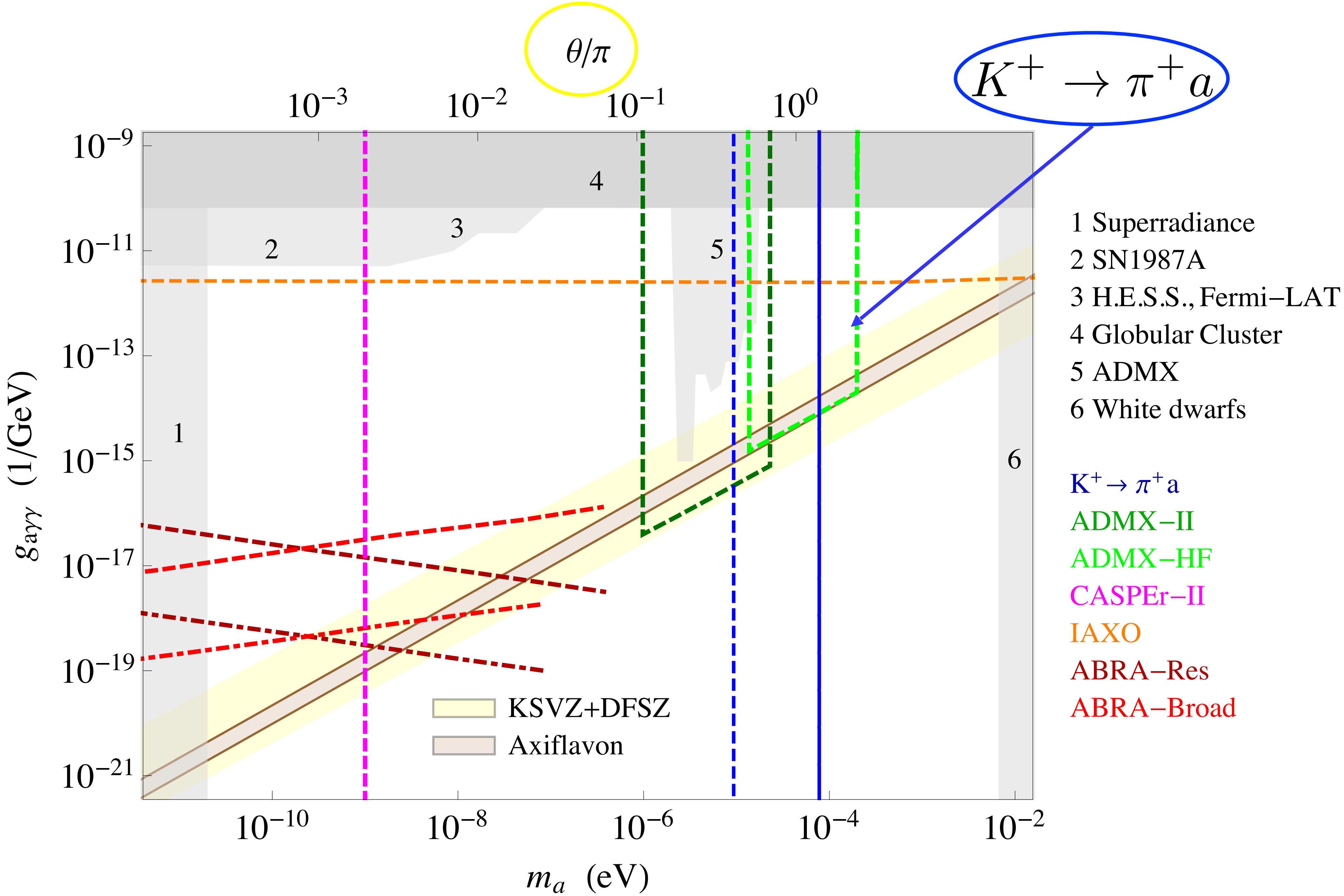
$\frac{1}{4} g_{a\gamma\gamma} a F \tilde{F}$

$m_a = 5.7\,\mu\text{eV}\left(\frac{10^{12}\text{GeV}}{f_a}\right)$

Axiflavon phenomenology

Axiflavon can be complementary tested at axion and flavour experiments!

$\frac{1}{4} g_{a\gamma\gamma} a F \tilde{F}$



$$m_a = 5.7\,\mu\text{eV}\left(\frac{10^{12}\text{GeV}}{f_a}\right)$$

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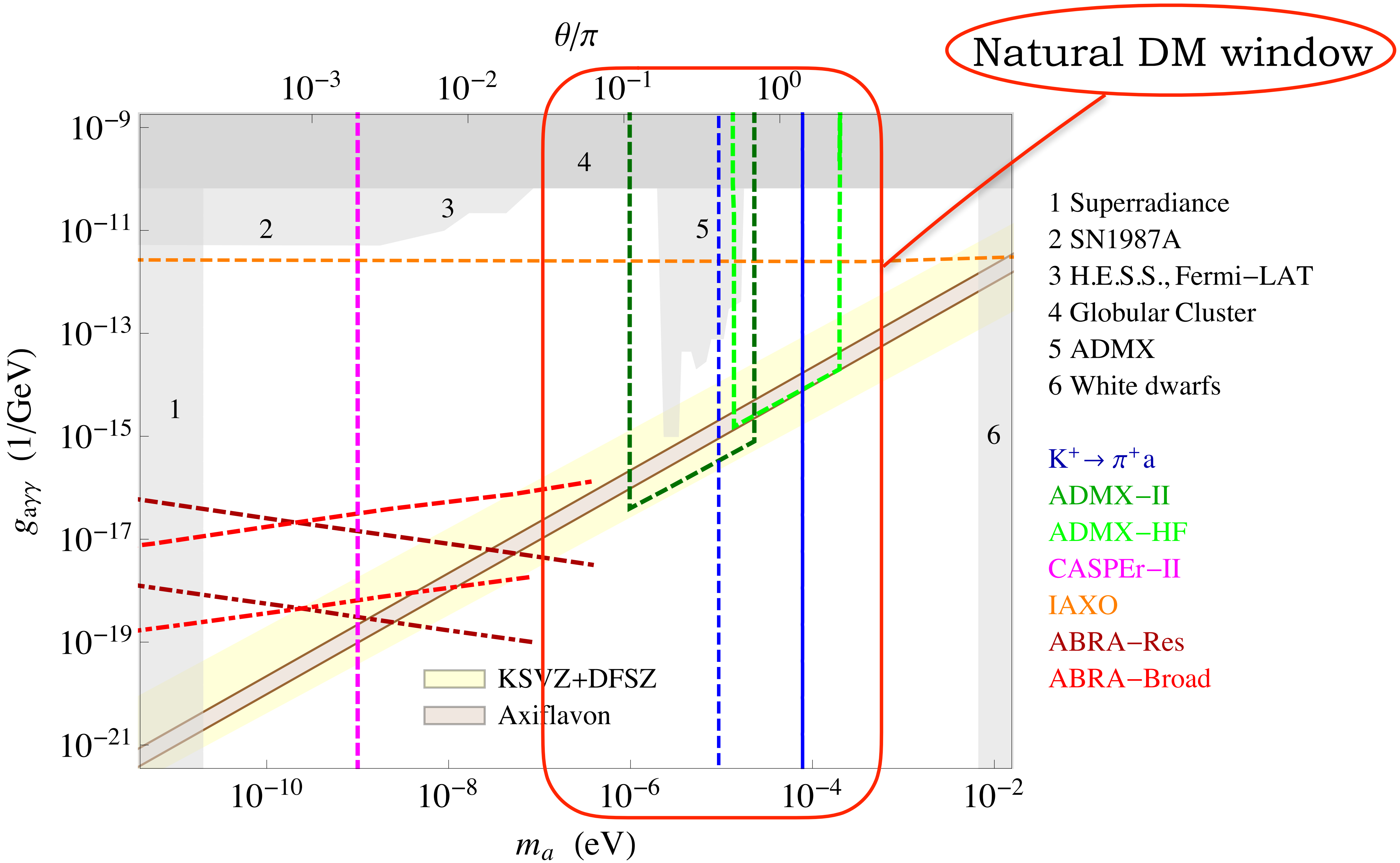

$\frac{1}{4} g_{a\gamma\gamma} a F \tilde{F}$

$$m_a = 5.7\,\mu\text{eV}\left(\frac{10^{12}\text{GeV}}{f_a}\right)$$

Model-Independent Bounds

Constrain effective couplings as good as possible

$$\mathcal{L}_{\text{eff}} = \frac{\partial_\mu a}{F_{ij}^V} \overline{f}_i \gamma^\mu f_j + \frac{\partial_\mu a}{F_{ij}^A} \overline{f}_i \gamma^\mu \gamma_5 f_j$$

Björkeroth, Chun, King '18

	$F_{q_1 q_2}^V$ [GeV]	$F_{q_1 q_2}^A$ [GeV]
sd	$6.9 \cdot 10^{11}$	$2.3 \cdot 10^6$
cu	$3.3 \cdot 10^5$	$2.4 \cdot 10^6$
bd	$1.0 \cdot 10^8$	$1.4 \cdot 10^6$
bs	$1.2 \cdot 10^8$	$3.0 \cdot 10^5$

(Feng, Moroi, Murayama, Schnapka '97)

from meson decays to PS + axion

$\text{BR}(D^+ \to \pi^+ a) < 1$ (no dedicated search)

$\text{BR}(B^+ \to K^+/\pi^+ a) < 4.9 \cdot 10^{-5}$ (CLEO '01)

from neutral meson mixing

$$\Delta M_K \approx \frac{f_K^2 M_K}{\left(F_{sd}^A\right)^2}$$

borrowed from R. Ziegler

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Plenty of Room for Improvement

Camalich, Vuong, RZ, Zupan, in progress...

- Use $\mathrm{BR}(K^+ \to \pi^+\pi^0 a) \leq 3.8 \cdot 10^{-5}$ E787 '01 → **gain** F^A_{sd} $\times 10$ (wrt $K-$mixing)
- Recast $D \to \tau\nu, \tau \to \pi\nu$ CLEO '08

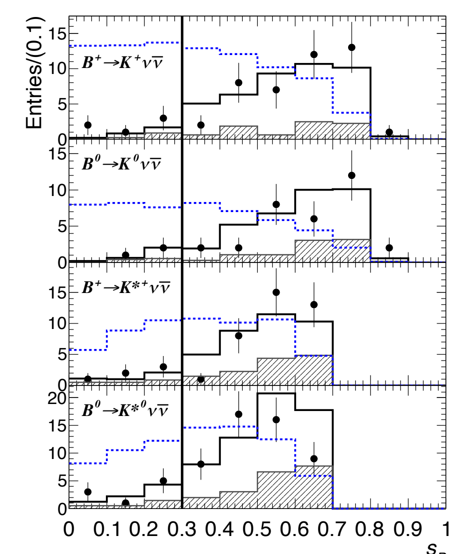
  $\mathrm{BR}(D^+ \to \pi^+ a) < 1.3 \cdot 10^{-4}$ → **gain** F^V_{cu} $\times 100$ (wrt total width)

  (see also Kamenik, Smith '11)
- Recast $B \to K/K^*\nu\bar{\nu}$ BaBar '13

  $\mathrm{BR}(B \to Ka) < 1.6 \cdot 10^{-5}$

  $\mathrm{BR}(B \to K^*a) < 1.0 \cdot 10^{-4}$ → **gain** F^A_{bs} $\times 1000$ (wrt B_s-mixing)

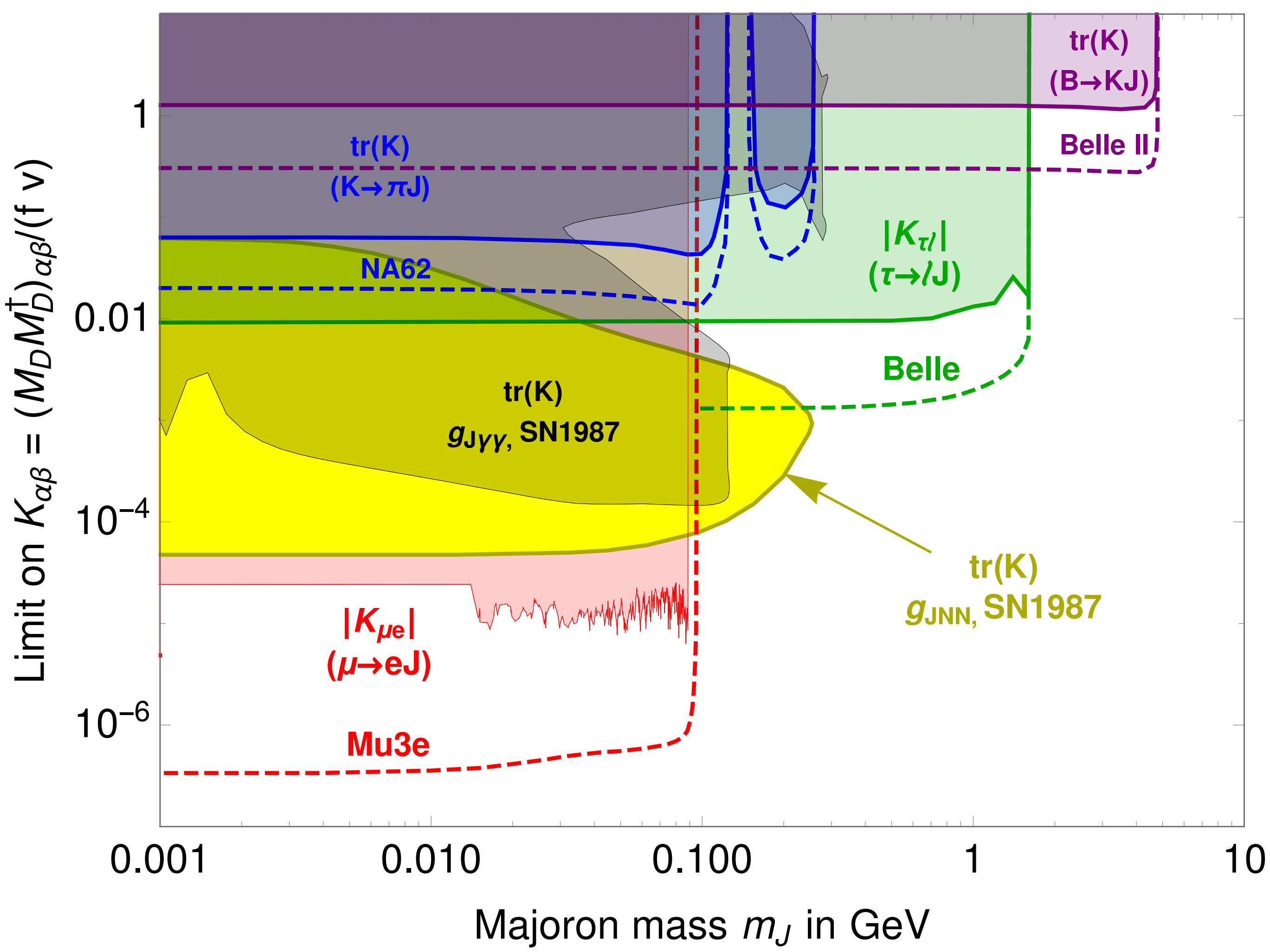
  (Belle cuts away $m^2_{\nu\bar{\nu}} = m^2_a \approx 0$ region)

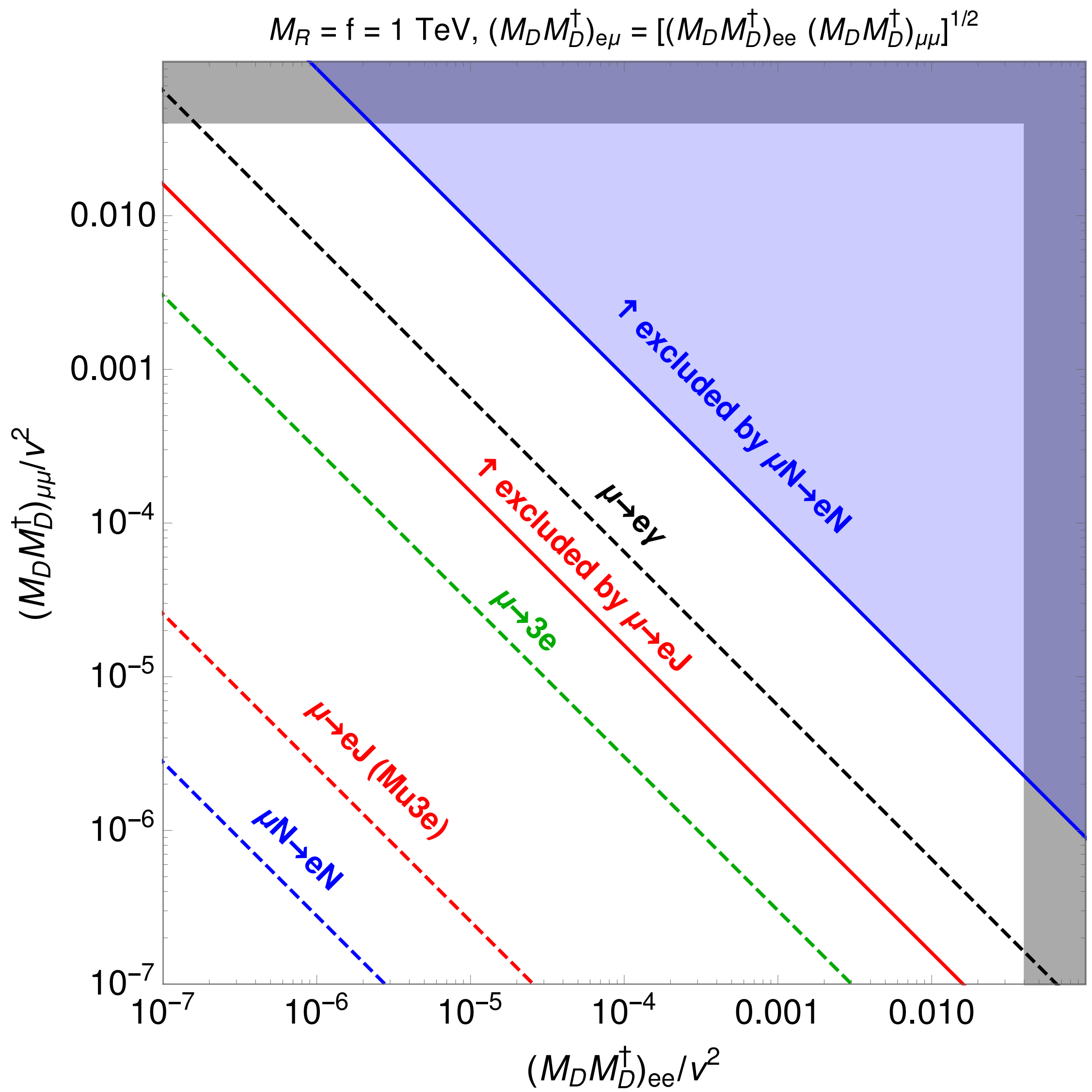


BaBar 1303.7465

Majoron results

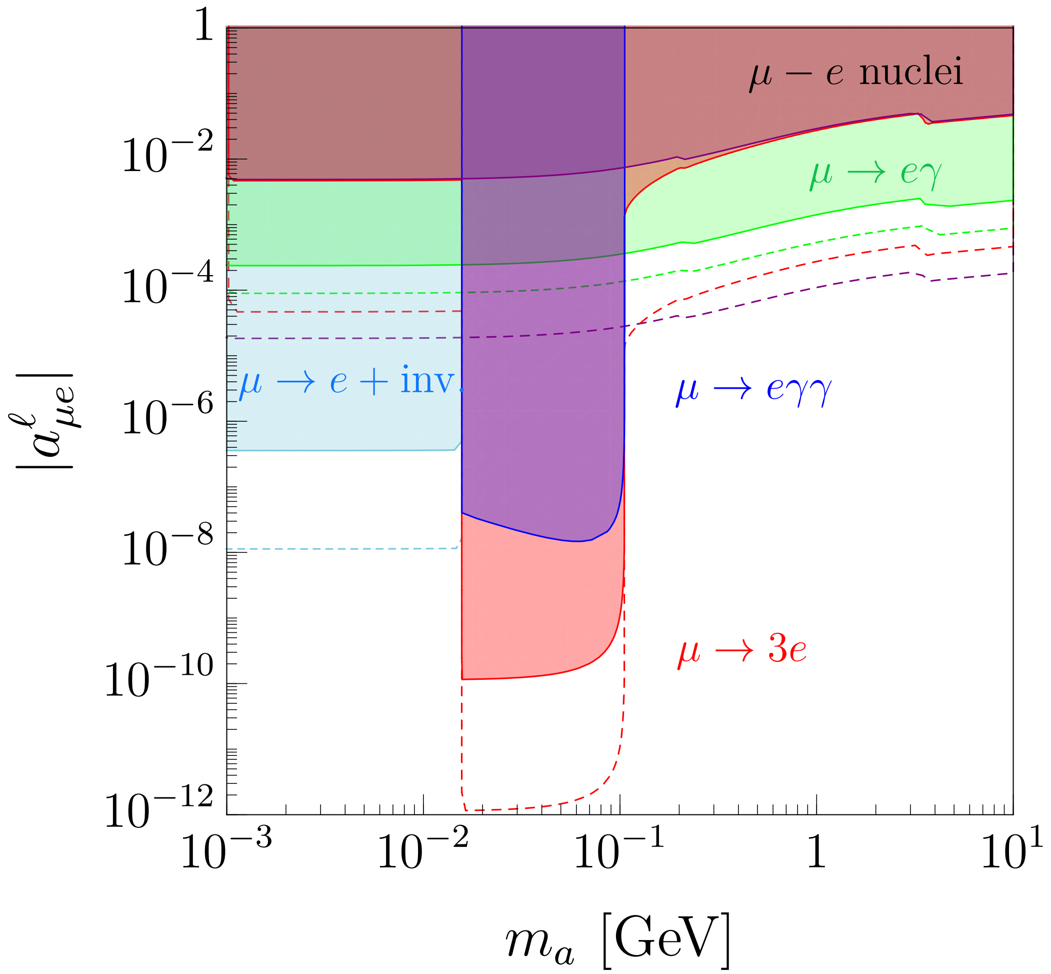
Heeck Patel '19

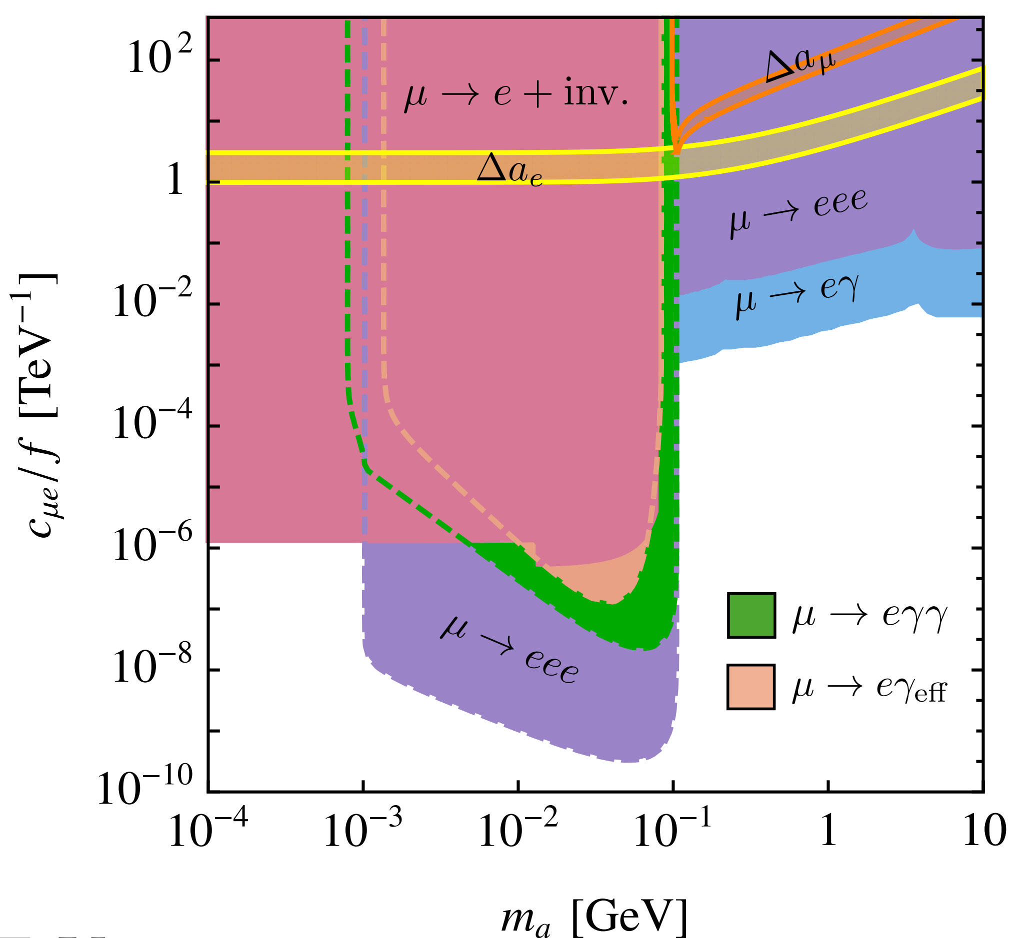




CLFV from short-lived ALPs

Bauer et al. '19
Cornella et al. '19





$c_{ee}/f = 1\,\text{TeV}$