Vietnam Flavour Physics Conference 2025

Introduction to BSM and Dark Sector Physics

Lorenzo Calibbi

南開大學
Nankai University

ICISE, Quy Nhon, August 22nd 2025

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Probing light new particles and high energy scales with flavour-violating processes

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Dark Matter exists! (About 27% of the energy of the universe)

DM direct detection searches and LHC searches for heavy new physics are giving increasingly tight constraints on WIMP models

This is why people increasingly focus *also* on other paradigms, *e.g.* axions, dark photons, light DM/light dark sectors etc.

Example: axion-like-particles (ALPs) (*often flavour-violating*) from a broad class of models with spontaneously broken global U(1)

Key example: axion-like particles

Pseudo Nambu-Goldstone bosons: naturally *light* & *feebly* interacting

Many scenarios motivated by outstanding problems of the SM:

Puzzle	Broken global U(1) symmetry	PNGB
• Neutrino masses →	Lepton Number	Majoron
• Strong CP problem →	Peccei-Quinn	Axion
• Flavour problem →	Flavour symmetry (Froggatt-Nielsen)	Familon

In general, the couplings to the SM fermions are of the form:

$$\mathcal{L}_{aff} = \frac{\partial_\mu a}{2 f_a}\, \bar{f}_i \gamma^\mu (C^V_{f_i f_j} + C^A_{f_i f_j} \gamma_5) f_j$$

Signature at flavour experiments: lepton/meson decays *into* ALPs

⇨ $K \to \pi a,\ D \to \pi a,\ B \to K a,\ \mu \to e a,\ \tau \to \mu a,\ \ldots$

Key example: axion-like particles

Pseudo Nambu-Goldstone bosons: naturally *light* & *feebly* interacting

Many scenarios motivated by outstanding problems of the SM:

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Interesting interplay with cosmology/astrophysics:

• ALPs can be DM candidates or serve as portals to a light dark sector:

$$\mathcal{L}_{a\chi\chi} = \frac{\partial_\mu a}{2 f_a} C^A_{\chi\chi}\, \bar{\chi}\gamma^\mu\gamma_5\chi$$

← dark fermion

• Bounds from star cooling/supernovae (if light and feeble enough)

General interactions to leptons (dimension 5 operators):

Shift symmetry (PNGB!) → mass arises 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

In general, these coupling are *lepton flavour violating* (LFV)

- That's natural if lepton U(1) charges are flavour non-universal
- Alternatively, flavour-violating couplings can be loop-induced

(for several explicit models see LC Redigolo Ziegler Zupan '20)

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

$$\Gamma(\ell_i \to \ell_j\, a) = \frac{1}{64\pi} \frac{m^3_{\ell_i}}{f_a^2} \left(|C^V_{\ell_i \ell_j}|^2 + |C^A_{\ell_i \ell_j}|^2 \right) \left(1 - \frac{m_a^2}{m^2_{\ell_i}} \right)^2$$

Feng et al. '97

Light NP coupling with hadrons

Flavour-violating axions/ALPs couplings to quarks

$$\mathcal{L}_{aff} = \frac{\partial_\mu a}{2 f_a}\, \bar{f}_i \gamma^\mu (C^V_{f_i f_j} + C^A_{f_i f_j}\gamma_5) f_j$$

vector coupling → $P_1 \to P_2 + a$ [e.g. $B \to K + a$]

axial coupling → $P_1 \to V_2 + a$ [e.g. $B \to K^* + a$]

(because of parity conservation of strong interactions)

Martin Camalich et al. '20

Decay	sd	cu	bd	bs
$\mathrm{BR}(P_1 \to P_2 + a)$	3×10^{-11} NA62 NEW!	No analysis	4.9×10^{-5} [90]	4.9×10^{-5} [90]
$\mathrm{BR}(P_1 \to P_2 + a)_{\mathrm{recast}}$	No need	8.0×10^{-6} [93]	2.3×10^{-5} [92]	7.1×10^{-6} [91]
$\mathrm{BR}(P_1 \to V_2 + a)$	3.8×10^{-5} [98]	No analysis	No analysis	No analysis
$\mathrm{BR}(P_1 \to V_2 + a)_{\mathrm{recast}}$	No need	No data	No data	5.3×10^{-5} [91]

to be updated soon

News from $K \to \pi + \mathrm{inv}$ (NA62) and $B \to K + \mathrm{inv}$ (Belle II)

→ talks by Jacopo Pinzino and Roberta Volpe

but there are still gaps...

Flavour-violating axions/ALPs couplings to quarks

$$\mathcal{L}_{aff} = \frac{\partial_\mu a}{2 f_a} \bar{f}_i \gamma^\mu (C^V_{f_i f_j} + C^A_{f_i f_j} \gamma_5) f_j$$

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Example: No dedicated searches for D to axion decays

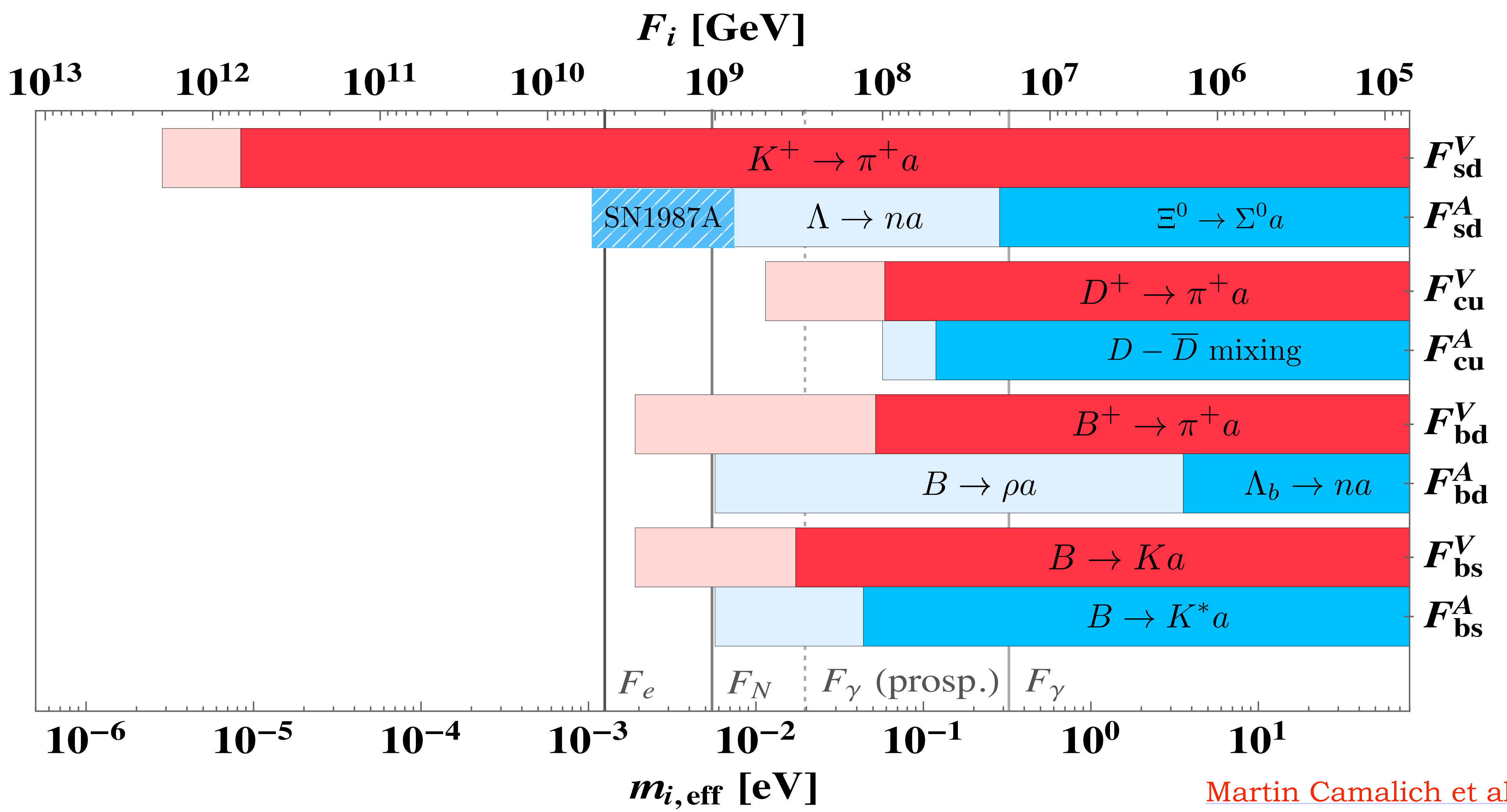
Recasting data from $D^+ \to \tau^+ (\to \pi^+ \nu)\, \nu$ (CLEO 2008):

$$\mathrm{BR}(D^+ \to \pi^+ a) < 8 \times 10^{-6}$$ → BESIII ? Belle II ?

Flavour-violating axions/ALPs couplings to quarks

$$\mathcal{L}_{aff} = \frac{\partial_\mu a}{2 f_a}\, \bar{f}_i \gamma^\mu (C^V_{f_i f_j} + C^A_{f_i f_j}\gamma_5) f_j$$

$$F^{V,A}_{f_i f_j} \equiv \frac{2 f_a}{C^{V,A}_{f_i f_j}}$$



Martin Camalich et al. '20

Another example: a flavour-violating Z'

Flavour non-universal **local** U(1) symmetry generating the hierarchies of fermion masses and mixing through the Froggatt-Nielsen mechanism

(anomalies cancelled by suitable UV completions Smolkovič Tammaro Zupan '19 Bonnefoy Dudas Pokorski '19)

Interactions of the new gauge boson Z' **flavour-violating** by construction:

$$\mathcal{L} = g_F Z'_\mu \Big[\overline{u}_\alpha \gamma^\mu (C^u_{L\,\alpha\beta} P_L + C^u_{R\,\alpha\beta} P_R) u_\beta + \overline{d}_\alpha \gamma^\mu (C^d_{L\,\alpha\beta} P_L + C^d_{R\,\alpha\beta} P_R) d_\beta + \overline{\ell}_\alpha \gamma^\mu (C^\ell_{L\,\alpha\beta} P_L + C^\ell_{R\,\alpha\beta} P_R) \ell_\beta + \bar{\nu}_\alpha \gamma^\mu C^\nu_{L\,\alpha\beta} P_L \nu_\beta \Big] ,$$

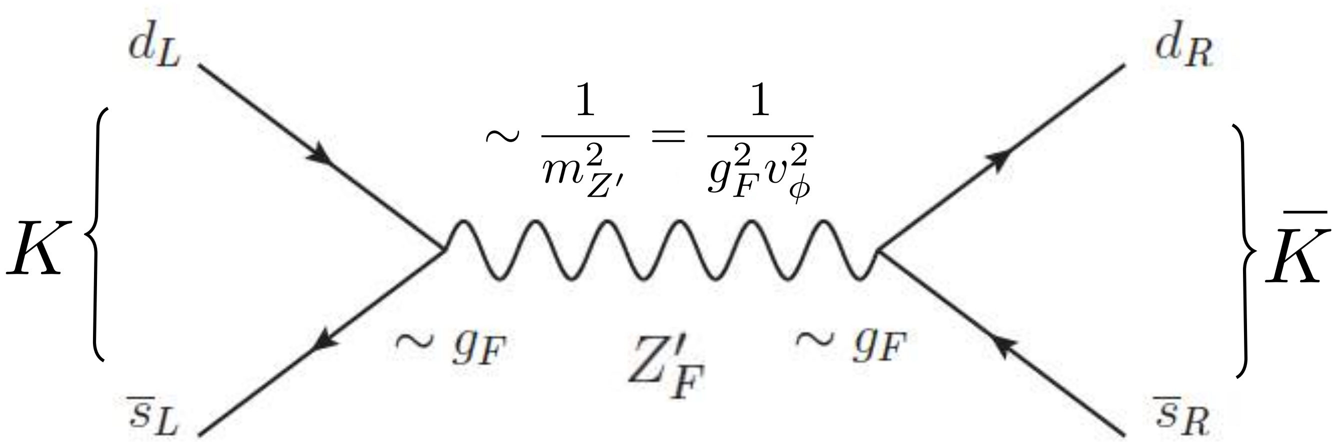
new U(1) gauge coupling

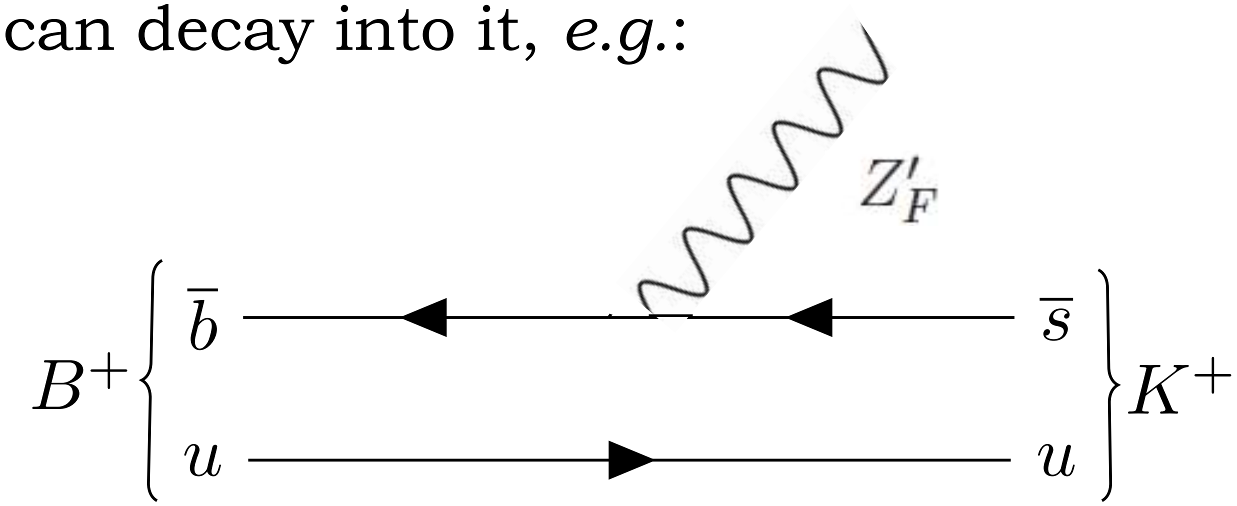
$$C^f_{L\,\alpha\beta} \equiv V^f_{\alpha i} \mathcal{Q}_{f_{L_i}} V^{f\,*}_{\beta i} \qquad C^f_{R\,\alpha\beta} \equiv W^f_{\alpha i} \mathcal{Q}_{f_{R_i}} W^{f\,*}_{\beta i} \qquad C^f_{V,A} = \frac{C^f_R \pm C^f_L}{2}$$

unitary rotations to the fermion mass basis

matrices of U(1) charges

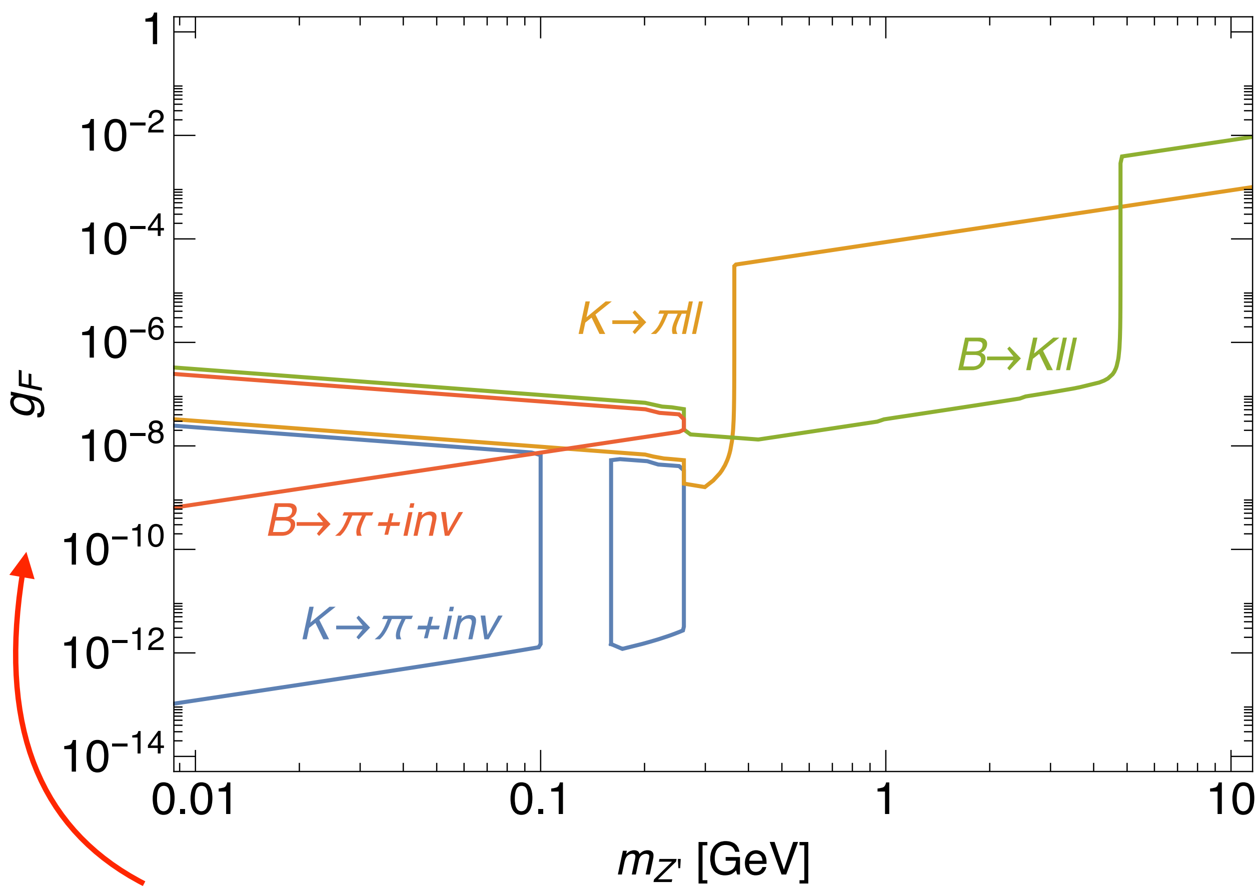
⇨ Z' mediates flavour-violating processes and, if light, mesons and leptons can decay into it, *e.g.*:



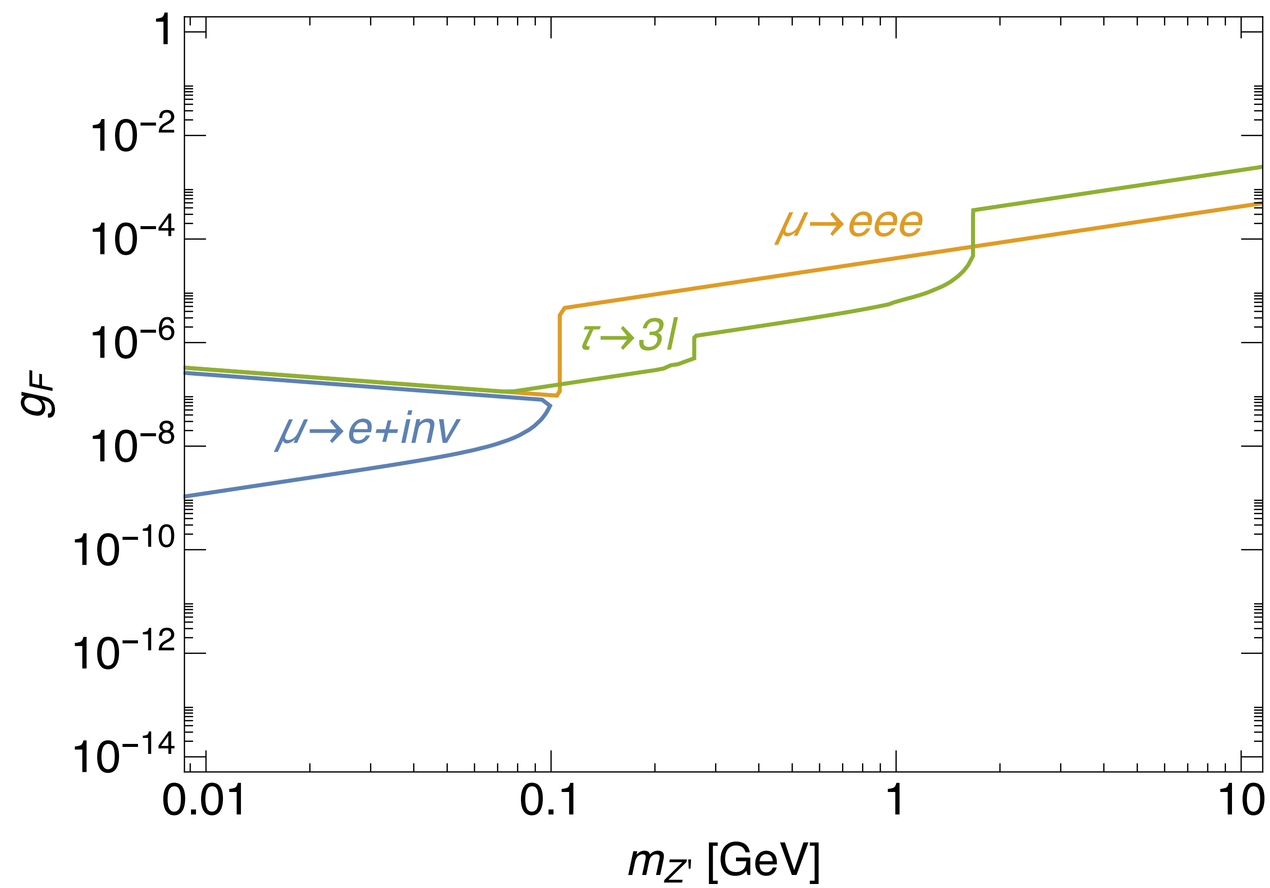


Flavour-violating Z' : flavour bounds

Meson decays into Z'



Lepton decays into Z'



U(1) coupling

$$m_{Z'} = \sqrt{2}\, g_F \langle\phi\rangle = g_F\, v_\phi$$

Z' boson mass

Flavour processes set stringent **lower bounds** on the U(1) breaking scale

$$K^+ \to \pi^+ Z': \; v_\phi \gtrsim 8.3\times 10^{10}\ \text{GeV}\,, \qquad B^+ \to K^+ Z': \; v_\phi \gtrsim 3.0\times 10^{7}\ \text{GeV}$$

$$\mu \to e Z': \; v_\phi \gtrsim 1.3\times 10^{7}\ \text{GeV}\,, \qquad \tau \to \ell Z': \; v_\phi \gtrsim 7.6\times 10^{5}\ \text{GeV}$$

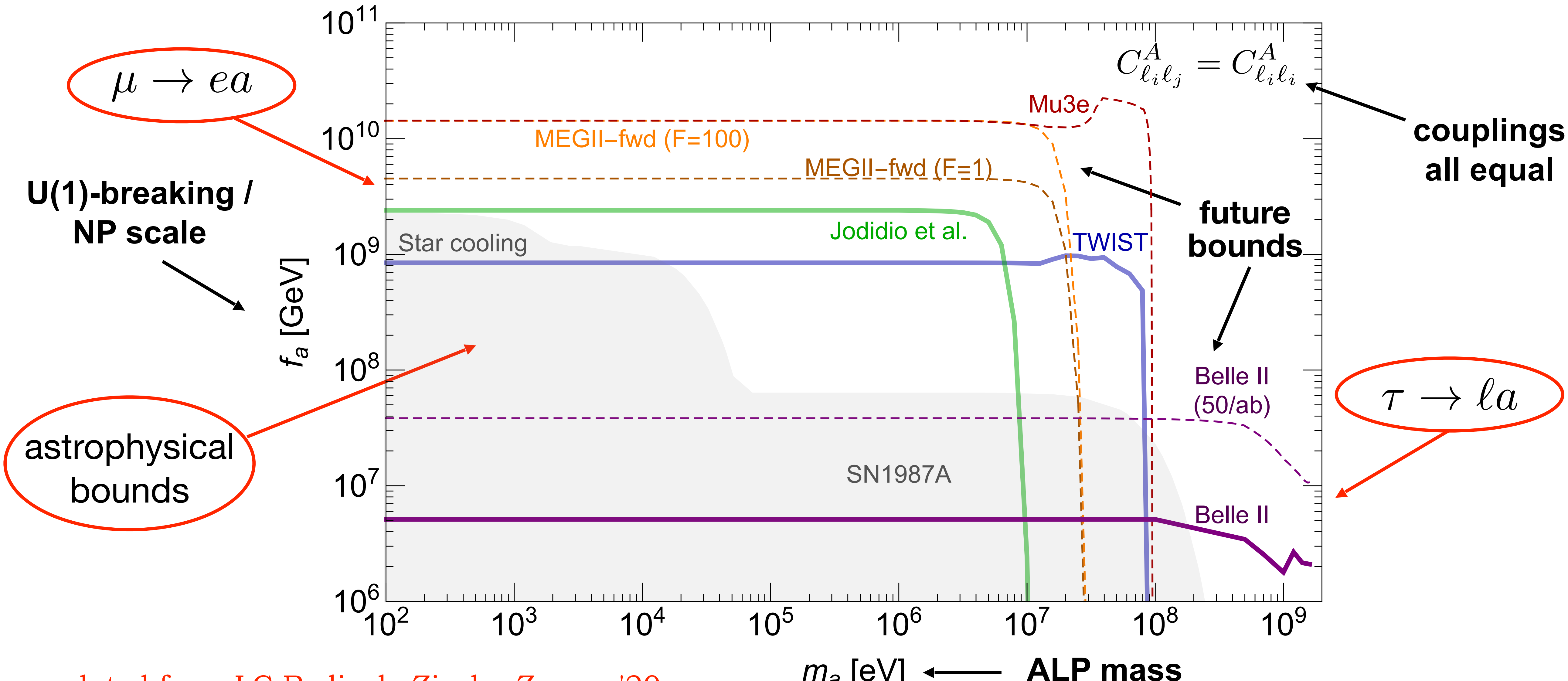
$$K-\bar{K}\ \text{mix.}: \; v_\phi \gtrsim 6.5\times 10^{5}\ \text{GeV}$$

Blasi LC Mariotti Turbang '24

Light NP coupling with leptons

Summary of searches for light *invisible* LFV ALPs

$$\mathcal{L}_{a\ell\ell} = \frac{\partial^\mu a}{2 f_a} \left(C^V_{ij}\, \bar{\ell}_i \gamma_\mu \ell_j + C^A_{ij}\, \bar{\ell}_i \gamma_\mu \gamma_5 \ell_j \right) \Rightarrow \Gamma(\ell_i \to \ell_j\, a) = \frac{1}{64\pi} \frac{m^3_{\ell_i}}{f_a^2} \left(|C^V_{\ell_i \ell_j}|^2 + |C^A_{\ell_i \ell_j}|^2 \right) \left(1 - \frac{m_a^2}{m^2_{\ell_i}} \right)^2$$



updated from LC Redigolo Ziegler Zupan '20

- Decays mediated by dimension-5 operators: one can reach NP scales even larger than $\mu \to e\gamma$, $\mu \to eee$ etc. (from dim-6 operators → Yamanaka-san talk)
- Mu/tau/astro interplay: if $m_a > m_\mu$ constraints mainly come from τ decays

$\mu \to e\, a$: signal and background

Signal: monochromatic positron with $p_e = \sqrt{\left(\frac{m_\mu^2 - m_a^2 + m_e^2}{2m_\mu}\right)^2 - m_e^2}$

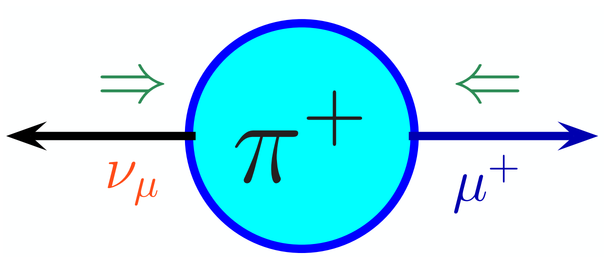
Differential decay rate: $$\frac{\mathrm{d}\Gamma(\ell_i \to \ell_j\, a)}{\mathrm{d}\cos\theta} = \frac{m_{\ell_i}^3}{32\pi F_{\ell_i\ell_j}^2}\left(1 - \frac{m_a^2}{m_{\ell_i}^2}\right)^2 \left[1 + 2P_{\ell_i}\cos\theta \frac{C^V_{\ell_i\ell_j} C^A_{\ell_i\ell_j}}{(C^V_{\ell_i\ell_j})^2 + (C^A_{\ell_i\ell_j})^2}\right]$$

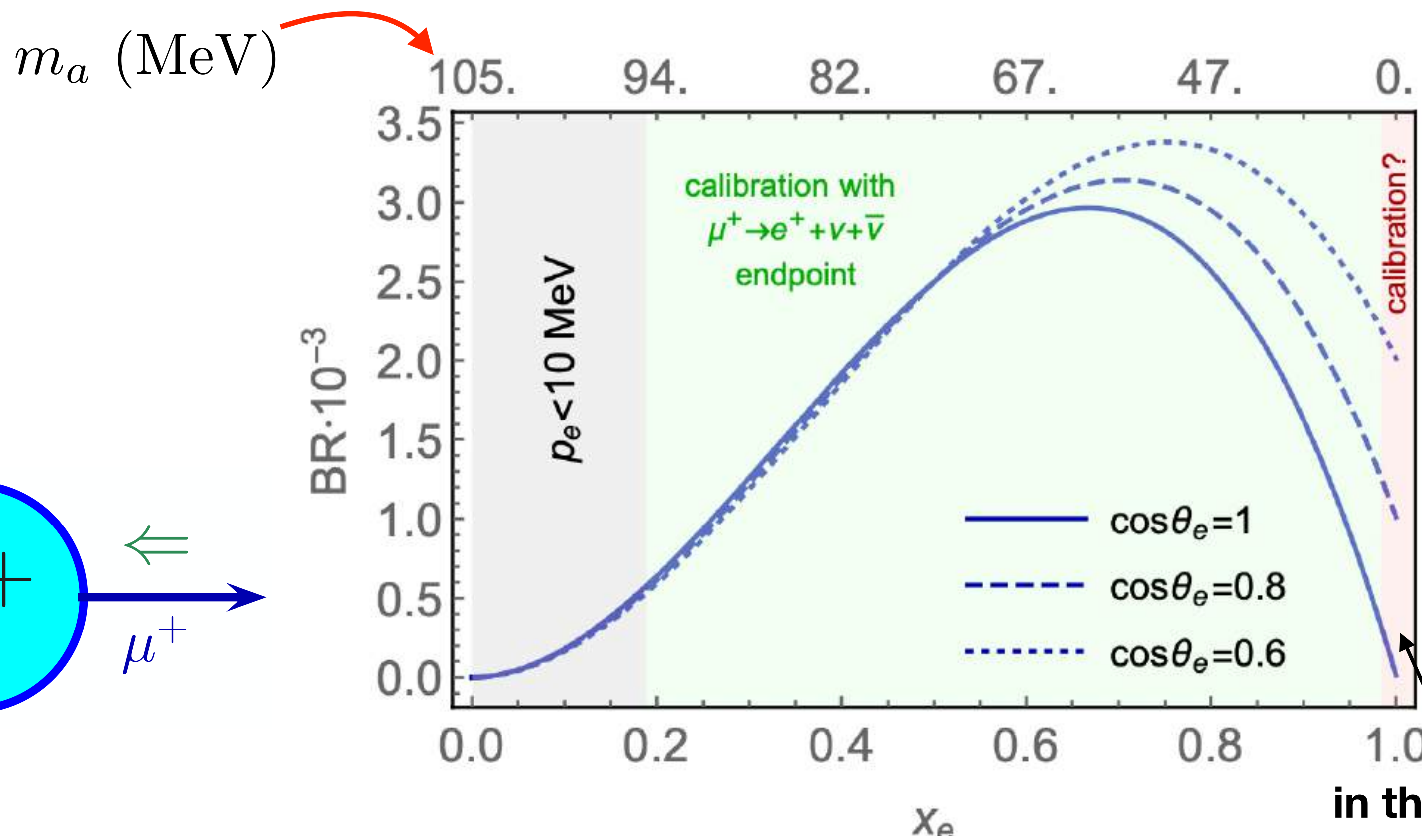
signal anisotropy depends on the chirality of the couplings

Michel spectrum: $$\frac{\mathrm{d}^2\Gamma(\mu^+ \to e^+\, \nu_e\, \bar\nu_\mu)}{\mathrm{d}x_e\, \mathrm{d}\cos\theta} \simeq \Gamma_\mu\left((3 - 2x_e) - P_\mu (2x_e - 1)\cos\theta\right) x_e^2$$ $x_e = \frac{2p_e}{m_\mu}$

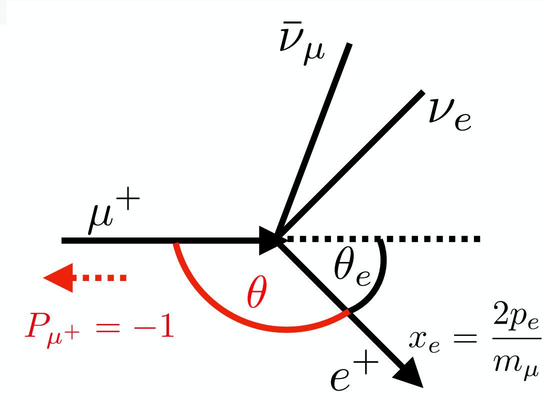
μ polarisation

And "surface" muons are highly polarised (produced by pion decays at rest on the surface of the production target) → the SM background can be suppressed





the bkd goes to zero
in the "forward"direction
(the direction opposite
to the muon polarization)



Currently strongest limit on $\mu \to e\, a$

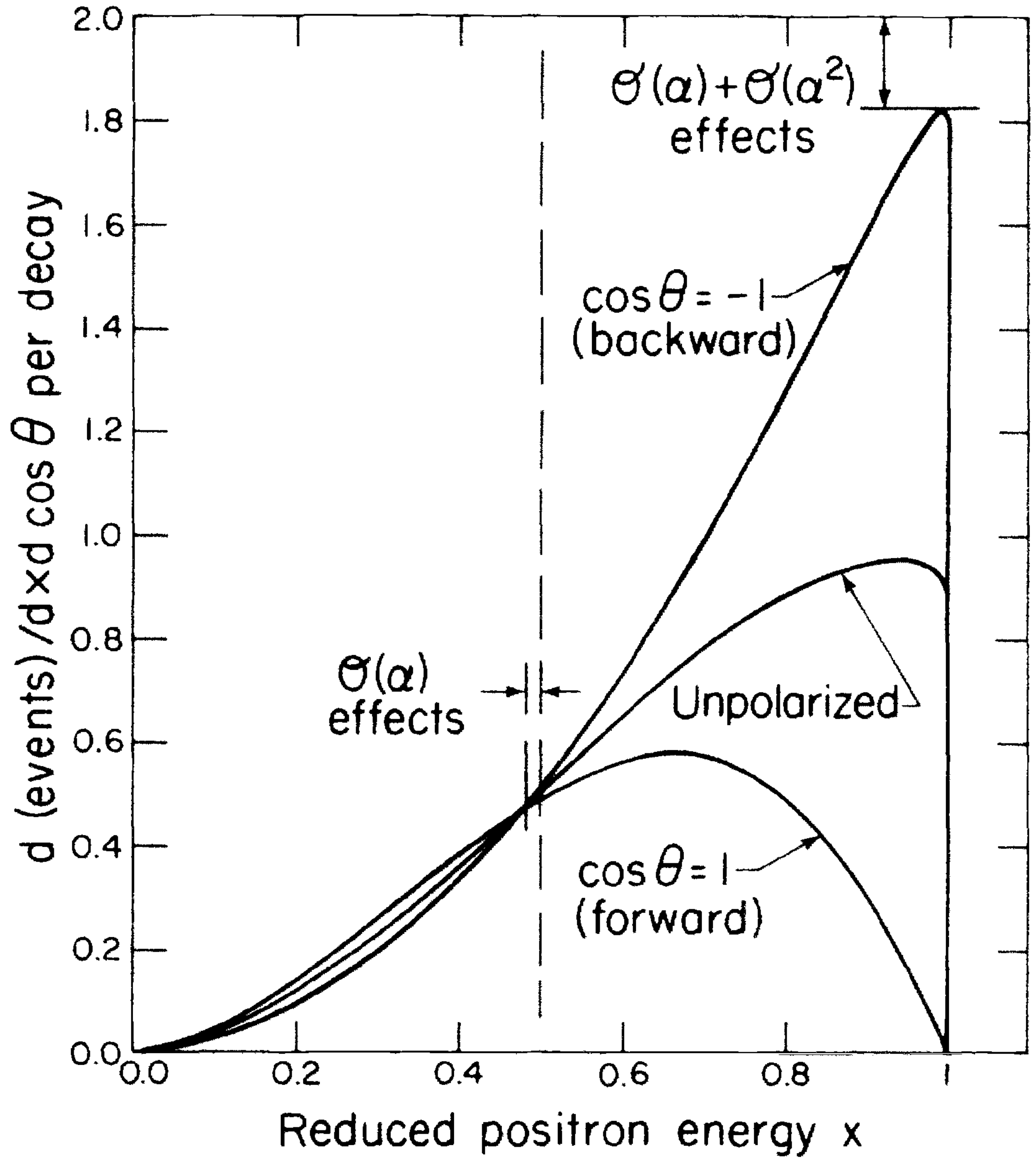
- Jodidio et al. (TRIUMF) 1986

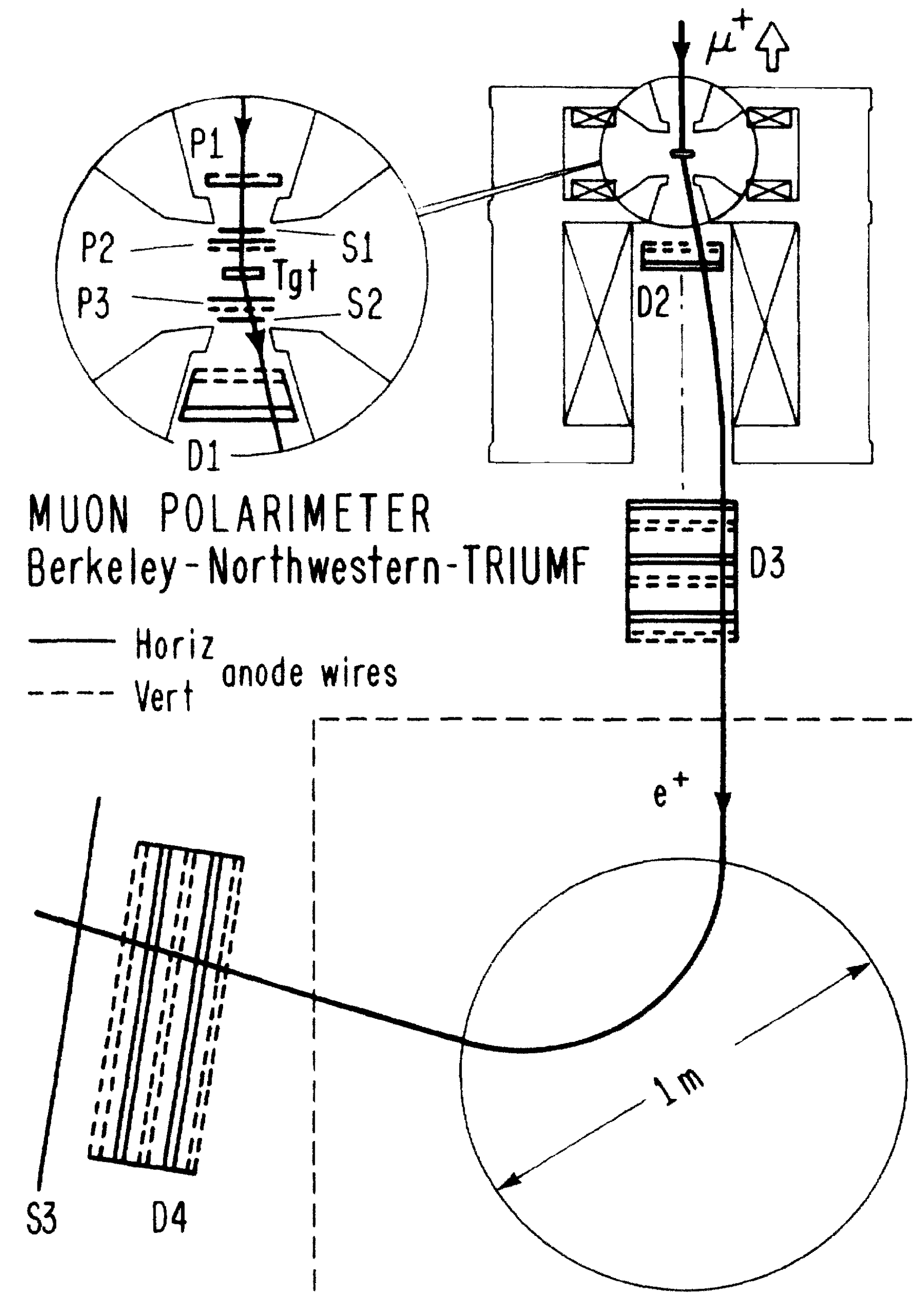
Search for RH currents with $1.8{\times}10^7$ polarised μ^+

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.)

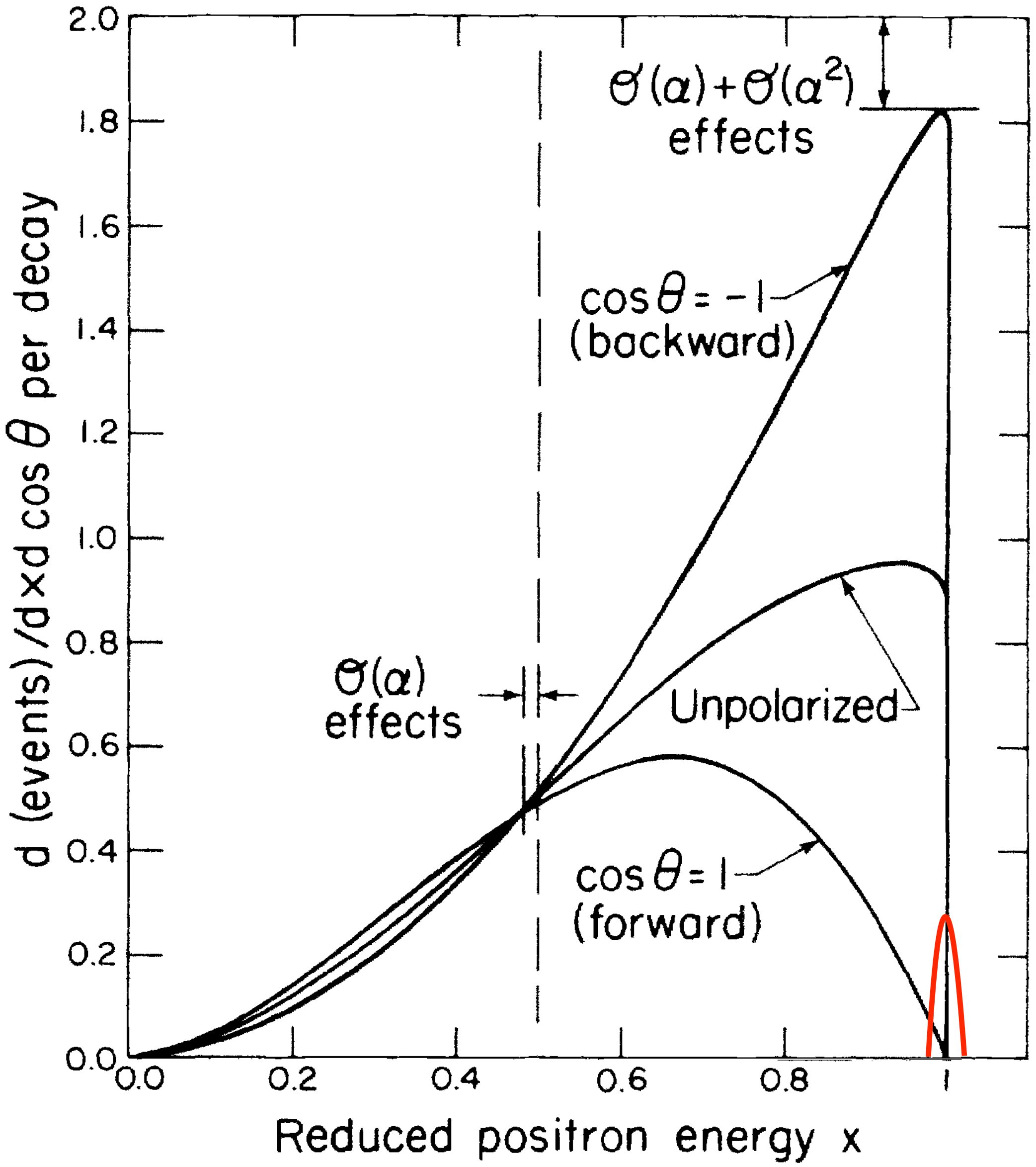
- Jodidio et al. (TRIUMF) 1986

Search for RH currents with 1.8×10^7 polarised 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

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

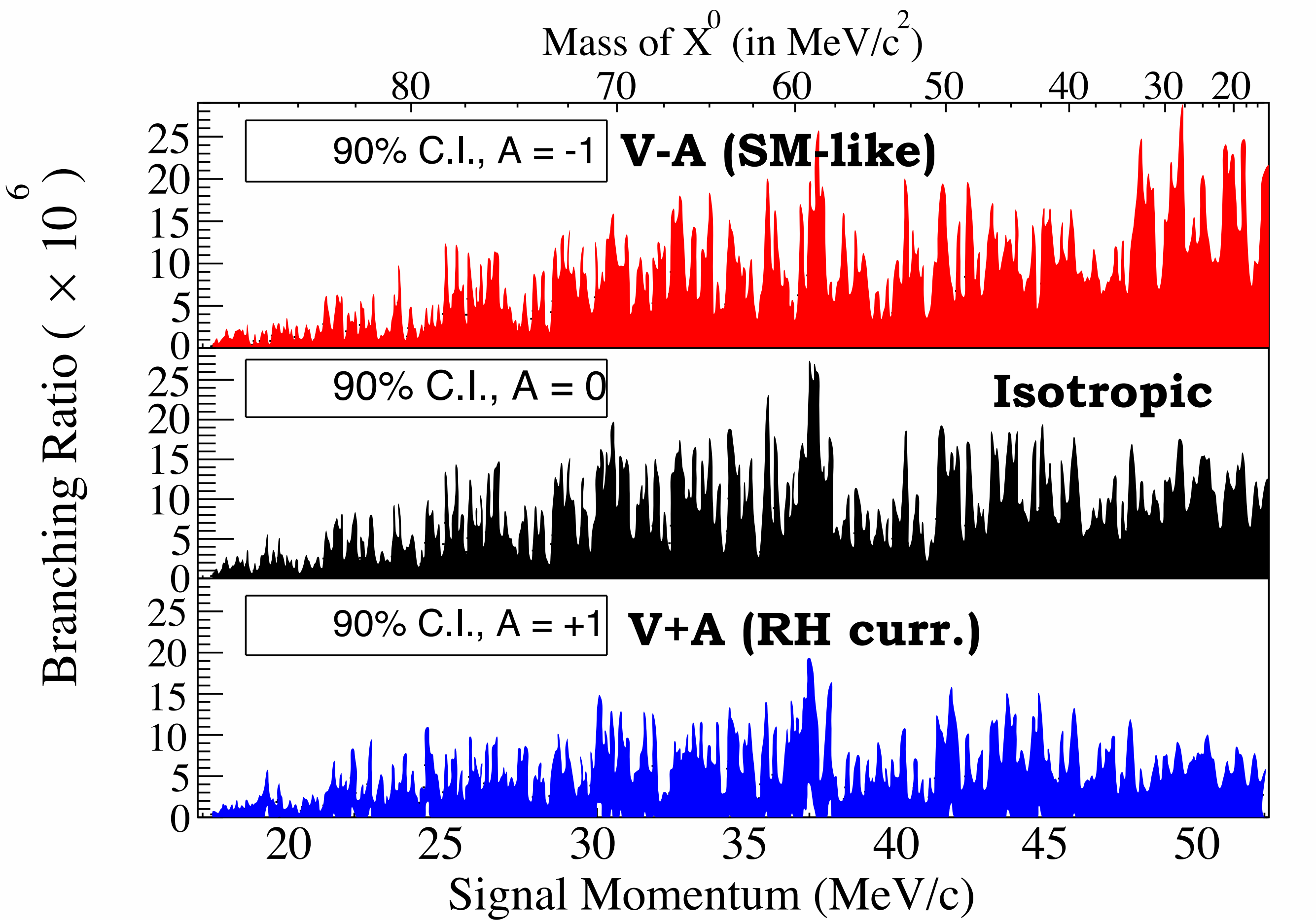
thus one gets

$$\Rightarrow \quad f_a/C^{V,A}_{e\mu} > 2.4\times 10^9 \ \text{GeV}$$

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

- 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 $m_a \approx 0$: $\mathrm{BR}(\mu \to ea) < 5.8 \times 10^{-5}$

$$\Rightarrow \quad f_a/C^{V,A}_{e\mu} > 10^9 \text{ GeV}$$

Present bounds based on old experiments and/or moderate luminosities (<10^9 total muon decays)

Modern facilities, e.g. $\pi E5$ beamline at PSI (where MEGII and Mu3e are located), can deliver >10^8 muons *per second*: next generation experiments must do better!

Many ideas and proposals at running and upcoming experiments:

MEG II → Toshiyuki Iwamoto's talk

- Add a forward calorimeter to perform a Jodidio-like search LC et al. '20
- Run with a dedicated trigger to search for $\mu \to ea\gamma$ Jho Knapen Redigolo '22

Mu3e → Tamasi Kar's talk

- Search performed on e^+ momentum histograms filled with *online* reconstructed short tracks Perrevoort (Mu3e) '18
- Search for $\mu \to 3ea$ from the internal conversion of virtual photon into e^+e^- Knapen et al. '23

COMET/Mu2e → Truong Nguyen's talk

- search for excess over the Michel spectrum, using data from calibration runs employing *positive* muon beams Hill Plestid Zupan '23
- enlarge the $\mu \to e$ conversion signal window coping with a large (~100kHz?) Michel background rate Xing et al. '22

cf. backup slides for details

Many ideas and proposals at running and upcoming experiments:

MEG

• Ad

• Ru

Mu3

• Se

rec

• Se e^-

'23

COM

• sea

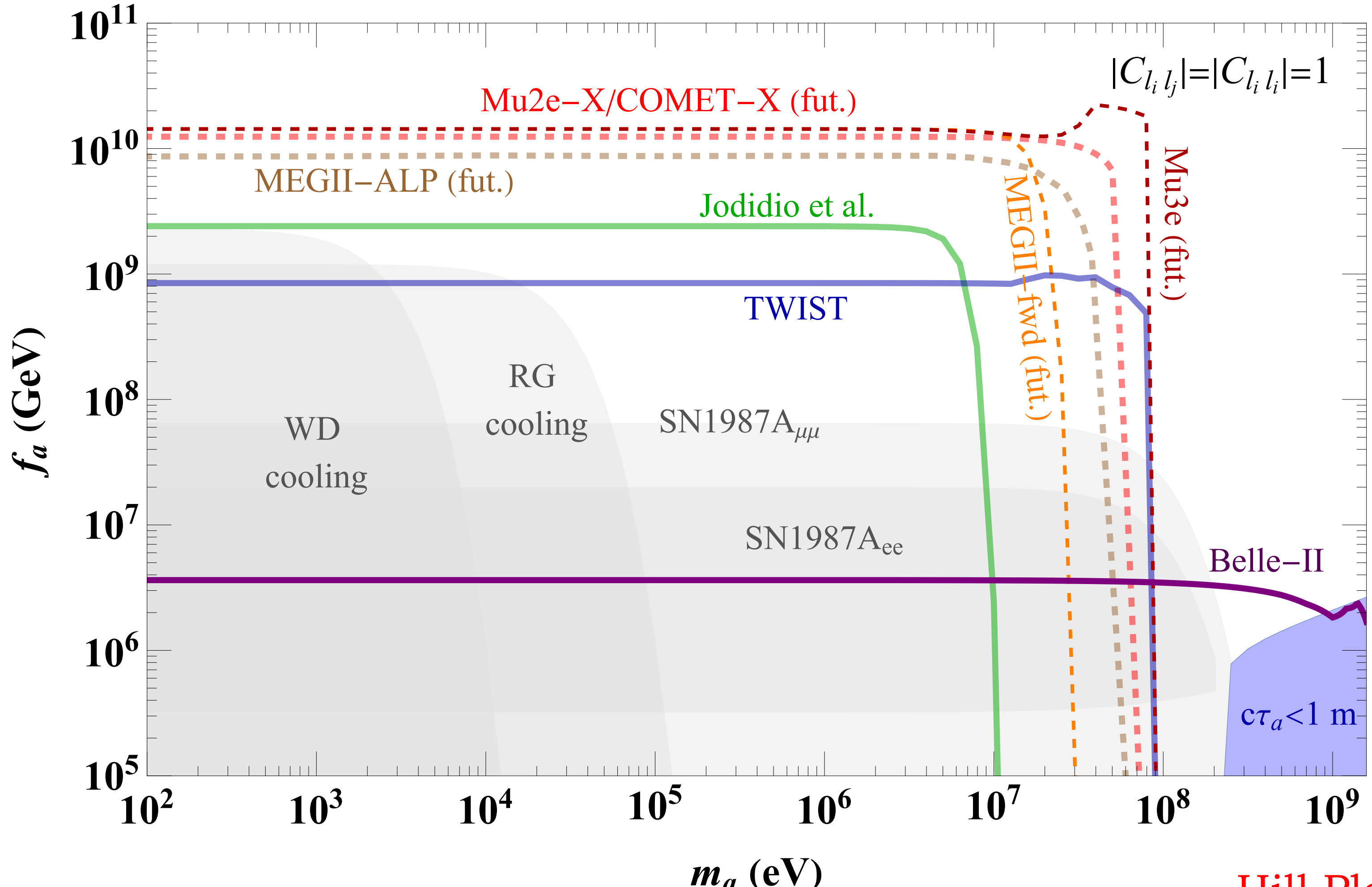
ru

• en z?)

Mi

Sensitivities up to BR$(\mu \to ea) \approx 10^{-8}$,

$f_a \approx 10^{10}$ GeV seem to be feasible!



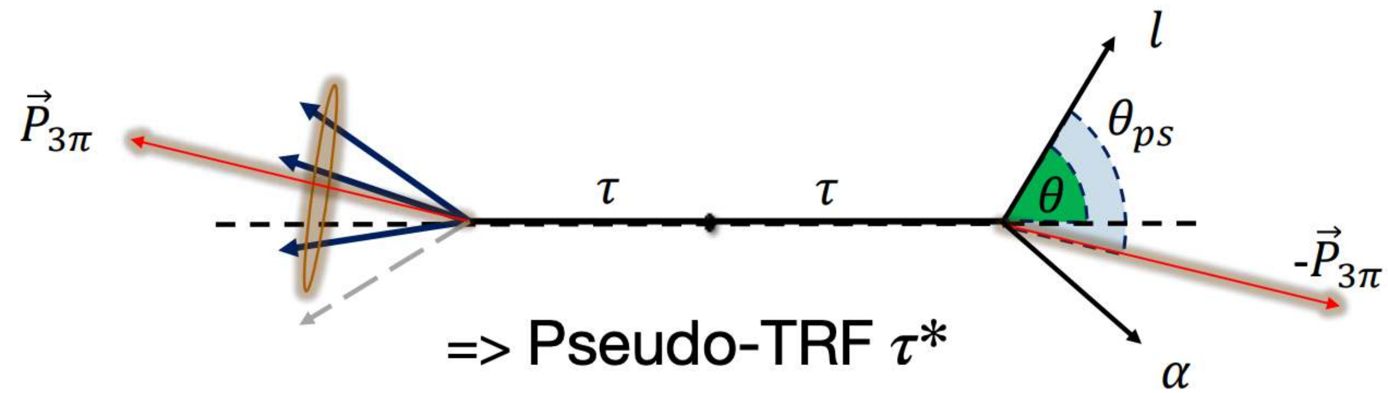
LC et al. '20

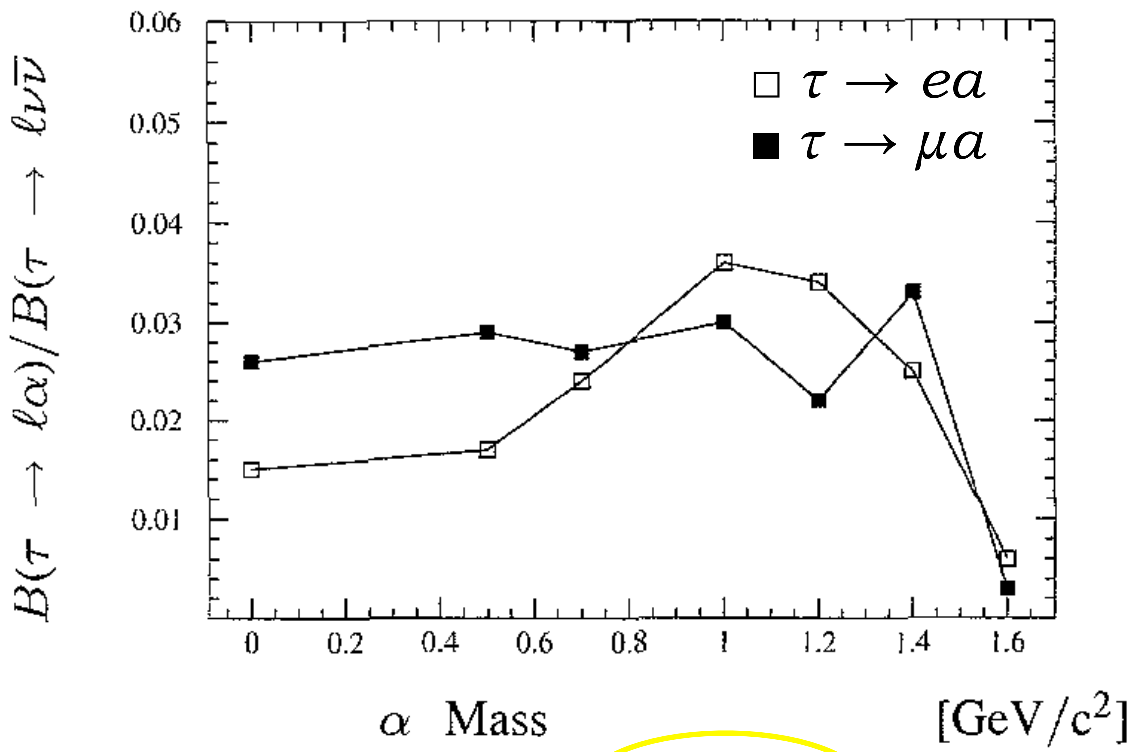
Hill Plestid Zupan '23

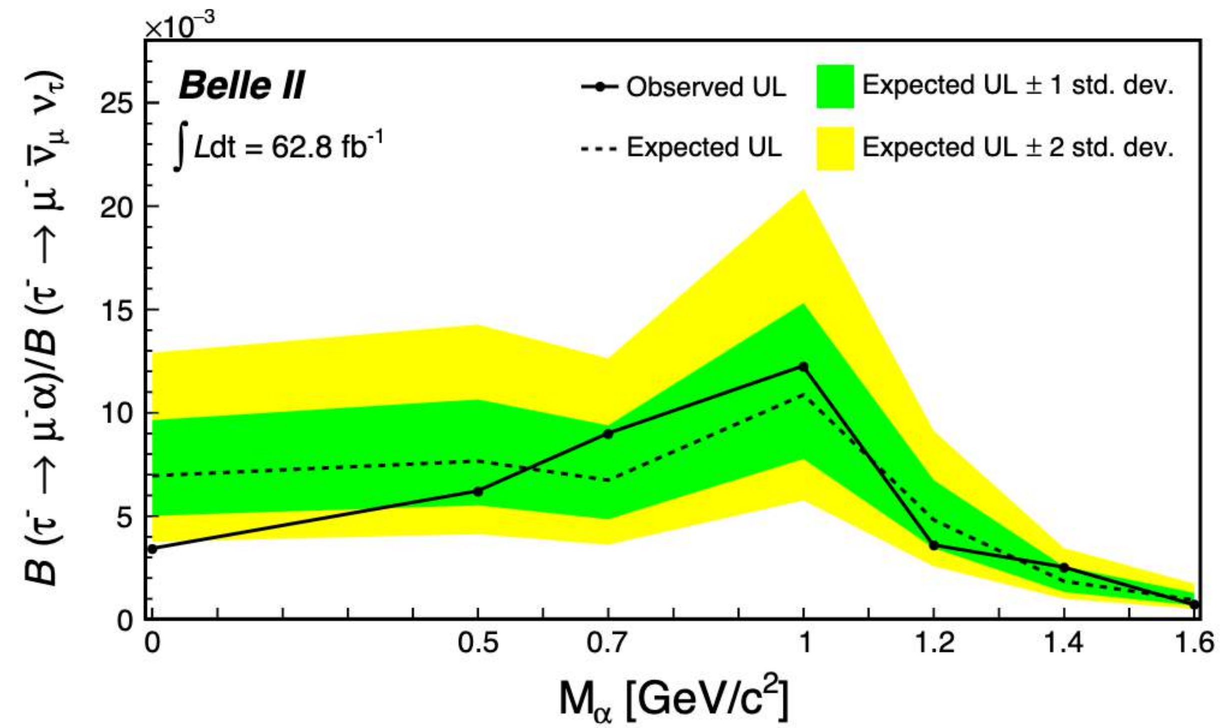
cf. backup slides for details

Present limits on $\tau \to e\, a$, $\tau \to \mu\, a$ (invisible a)

A challenging search:
tau momentum / rest frame
cannot be exactly reconstructed
BG: ordinary $\tau \to \ell \nu \bar{\nu}$







ARGUS 1995 (472 pb^{-1}) → Belle II 2023 (62.8 fb^{-1})

up to O(10) improvement!

$m_a \approx 0$:

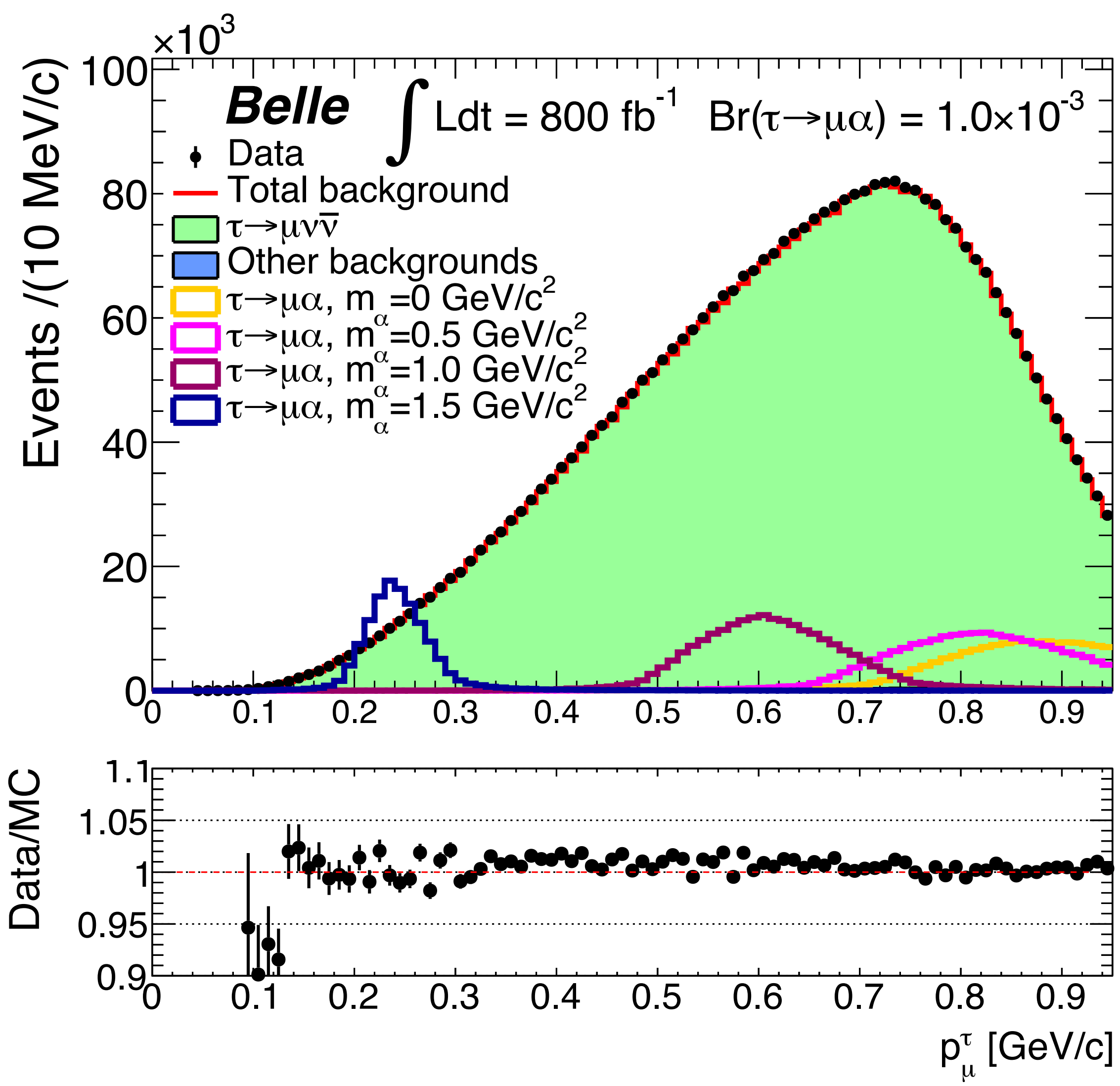
$$\mathrm{BR}(\tau \to \mu\, a) < 4.7 \times 10^{-4}\ (90\%\ \mathrm{CL}) \quad \Rightarrow \quad f_a/C^{V,A}_{\mu\tau} > 5.1 \times 10^{6}\ \mathrm{GeV}$$

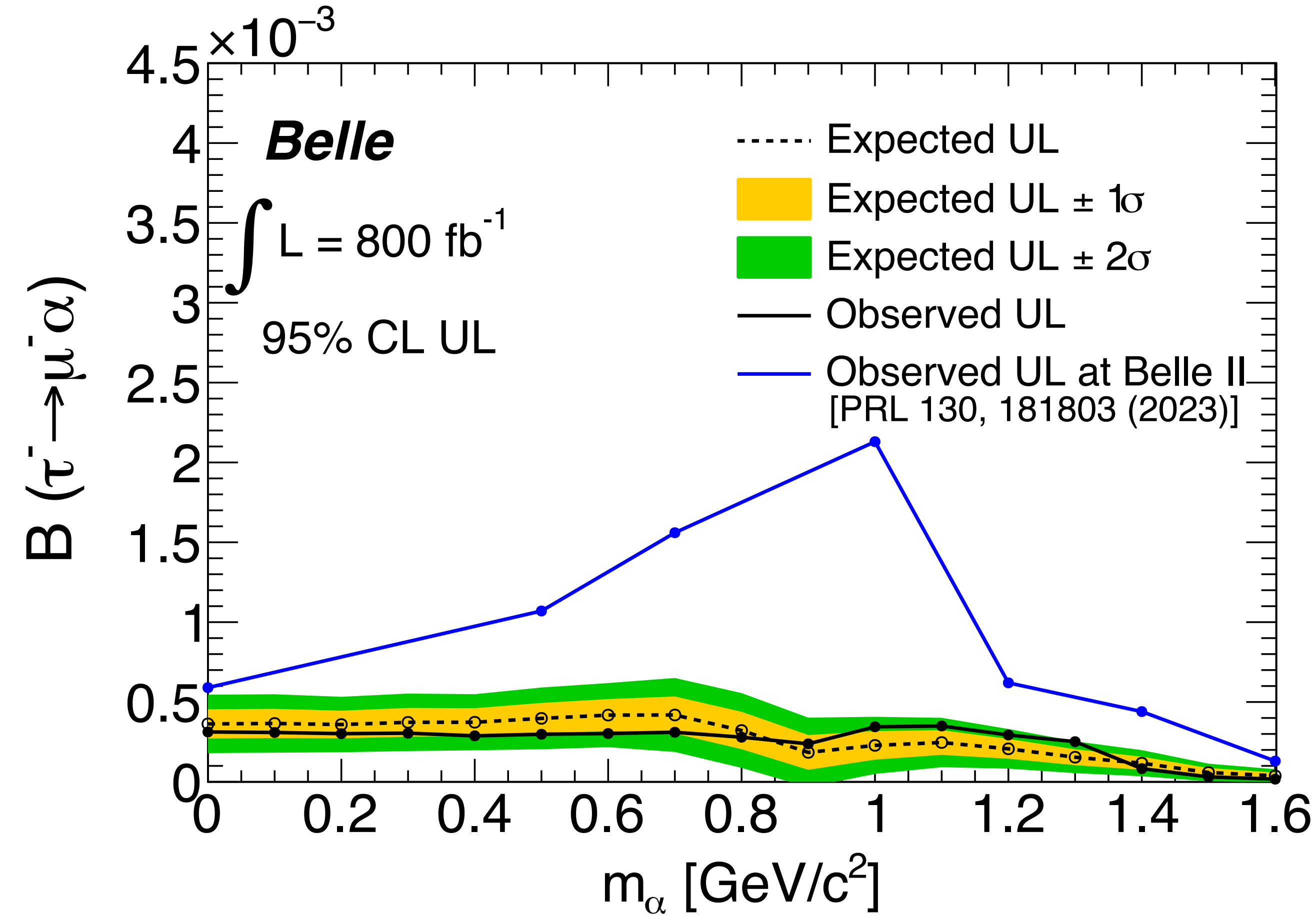
$$\mathrm{BR}(\tau \to e\, a) < 7.6 \times 10^{-4}\ (90\%\ \mathrm{CL}) \quad \Rightarrow \quad f_a/C^{V,A}_{e\tau} > 4.0 \times 10^{6}\ \mathrm{GeV}$$

Present limits on $\tau \to e\, a$, $\tau \to \mu\, a$ (invisible a)

A challenging search:

• NEW! Belle 2025 (800 fb^{-1}) → talk by Jing-Ge Shiu



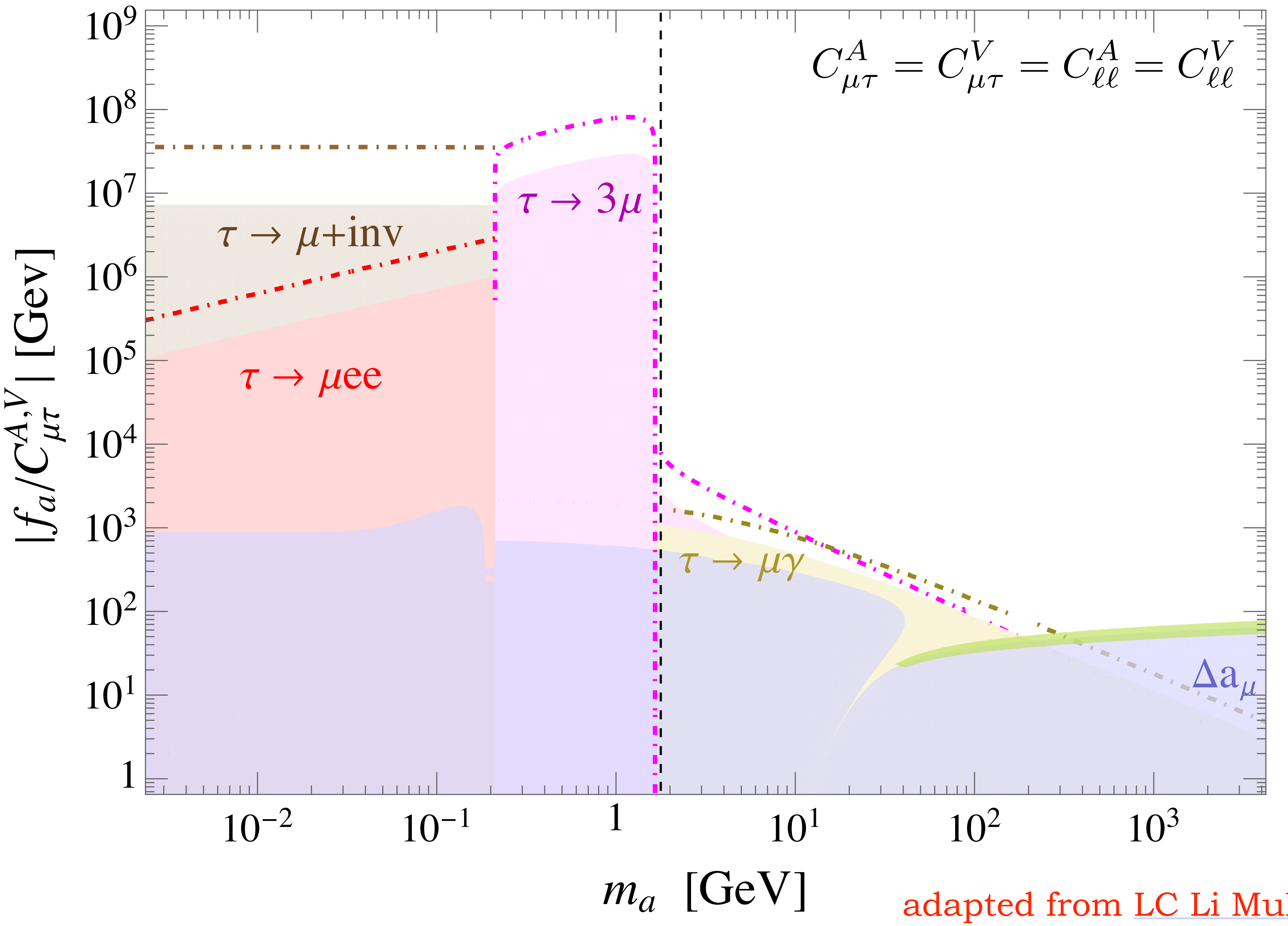


$m_a \approx 0$: $\mathrm{BR}(\tau \to e\, a) < 7.6 \times 10^{-4}$ (90% CL) $\Rightarrow$ $f_a/C^{V,A}_{e\tau} > 4.0 \times 10^6$ GeV

ALP-mediated tau LFV

If the ALP is not that light nor long-lived, it can decay on-shell (or off-shell) back to leptons: $\tau \to \mu\, a^{(*)} \to \mu\ell\ell$

(or mediate radiative processes)

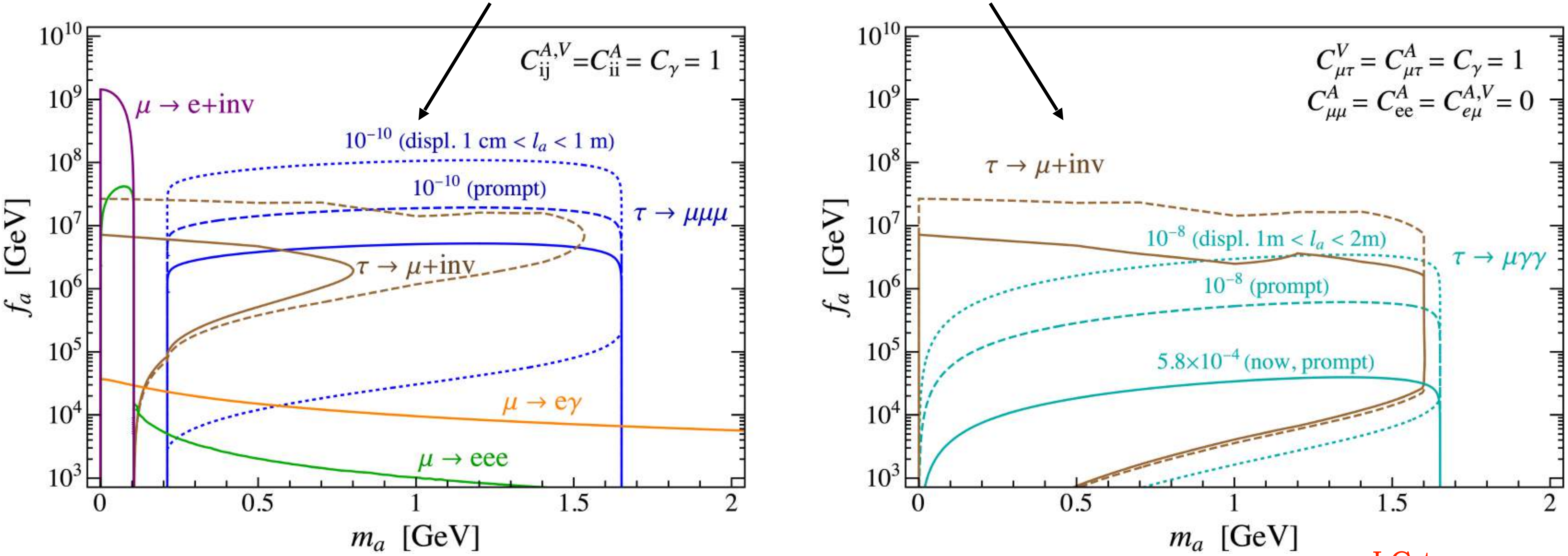


adapted from LC Li Mukherjee Yang '24
(see also Cornella Paradisi Sumensari '19)

If the ALP is not that light nor long-lived, it can decay on-shell (or off-shell) back to leptons: $\tau \to \mu\, a^{(*)} \to \mu\ell\ell$

(or mediate radiative processes)

Belle II prospects for long-lived/displaced ALPs



LC to appear

Interplay between visible, invisible, and displaced searches!

What about Dark Matter?

- Obvious requirement, cosmological lifetime

$$\frac{H_0}{\Gamma_{\rm tot}} = H_0 \tau_a > 1$$

- More stringent bound: extragalactic background light (from $a \to \gamma\gamma$)

Coupling to photons $(m_a \ll m_{\ell_i})$: $\mathcal{L}_{\rm eff} = E_{\rm UV} \frac{\alpha_{\rm em}}{4\pi} \frac{a}{f_a} F \tilde{F}$

depends on UV completion,
e.g. anomaly coefficient (QCD axion: $E_{\rm UV} = E/2N$)

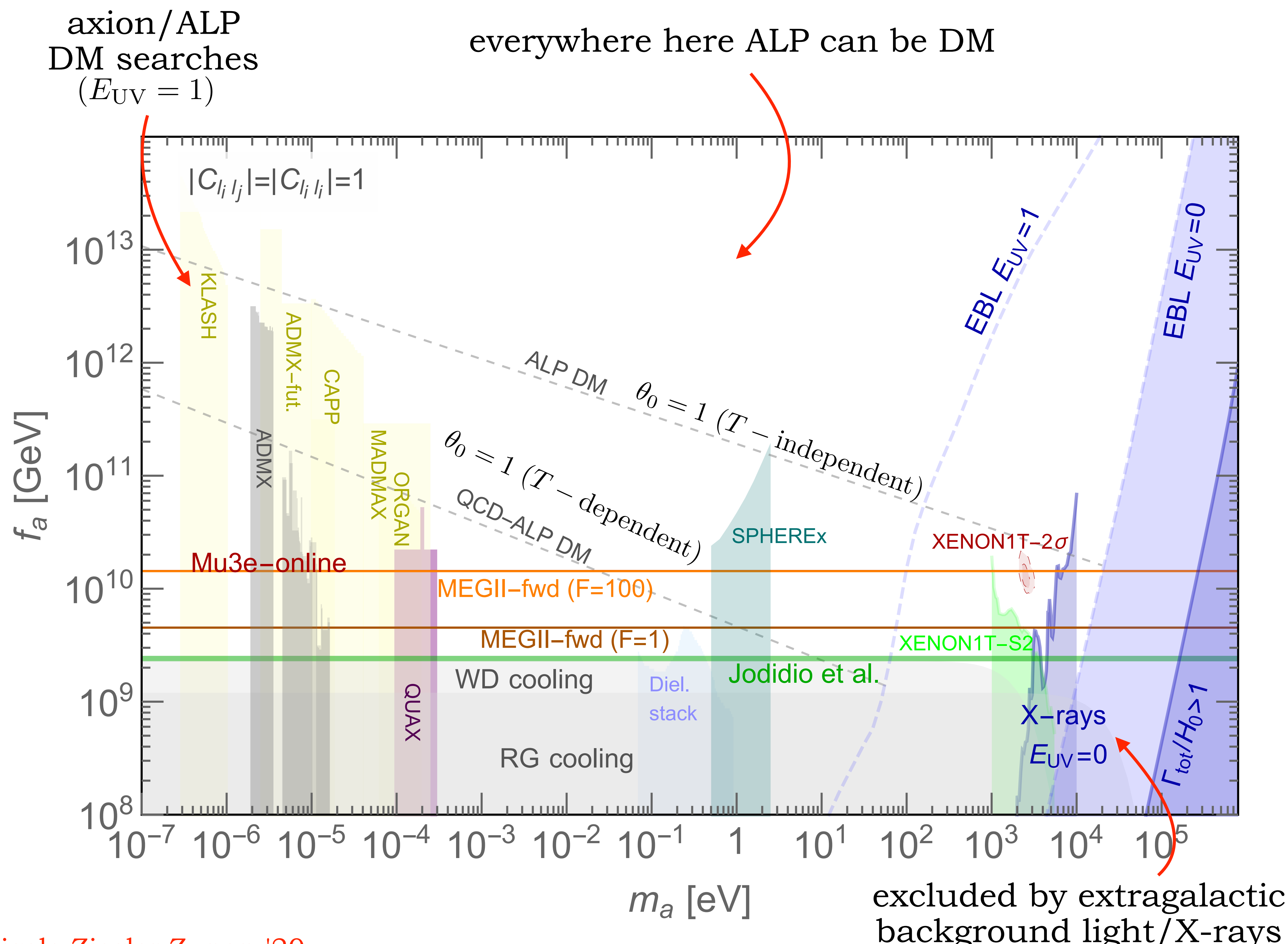
- Production: misalignment mechanism

$$\Omega_a^{T\text{-indep.}} h^2 = 0.12 \times 10^{-2} \sqrt{\frac{m_a}{\rm eV}} \left(\frac{f_a}{10^{10}{\rm GeV}}\right)^2 \left(\frac{\theta_0}{\pi}\right)^2 \left(\frac{90}{g_*(T_{\rm osc})}\right)^{1/4}$$

misalign. angle

it can be enhanced if ALP mass suppressed at finite temperature (e.g. QCD axion)

ALP dark matter



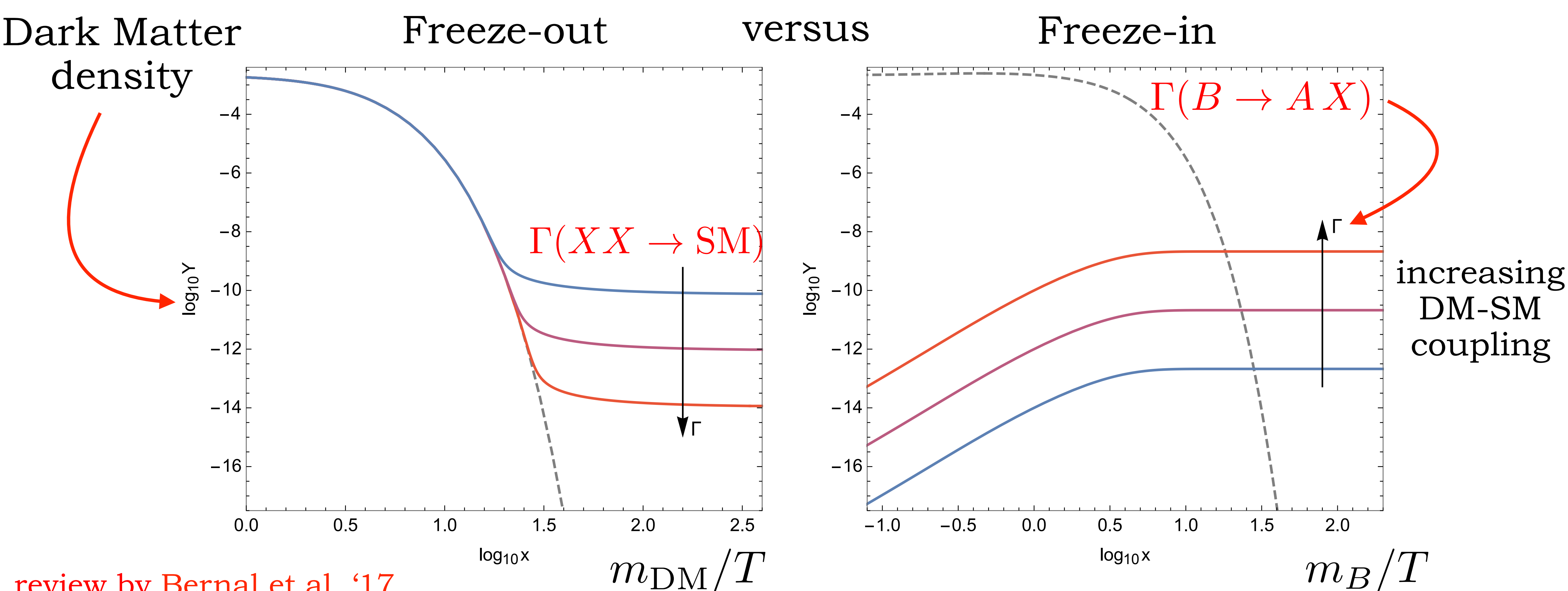
LC Redigolo Ziegler Zupan '20

LFV dark matter production?

What if $\mu \to ea$, $\tau \to \mu a$ also produce DM ALPs in the early universe, via the *freeze-in* mechanism? Panci Redigolo Schwetz Ziegler '22

Freeze-in: a production mechanism for DM that was never in thermal equilibrium with the Standard Model bath (because too *feebly-coupled*), but can be produced via scattering or decays of bath particles

Hall Jedamzik March-Russell West '09



review by Bernal et al. '17

What if $\mu \to ea$, $\tau \to \mu a$ also produce DM ALPs in the early universe, via the *freeze-in* mechanism?

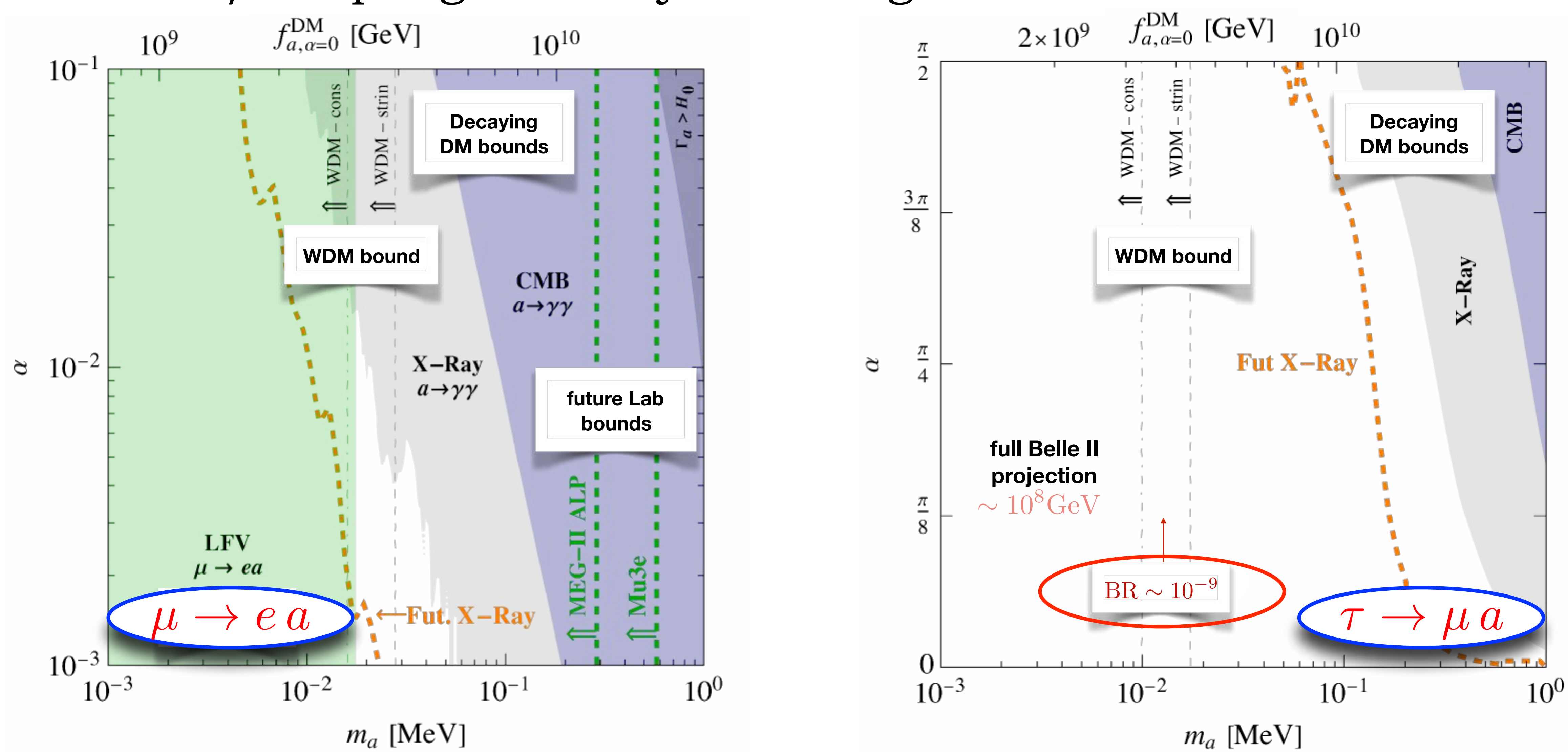
$$\mathcal{L}_a = \frac{\partial_\nu a}{2 f_a}\left[\cos\alpha \cdot \bar{\tau}\gamma^\nu\gamma_5\mu + \sin\alpha \cdot \bar{\tau}\gamma^\nu\gamma_5\tau - \sin\alpha \cdot \bar{\mu}\gamma^\nu\gamma_5\mu\right] - \frac{1}{2}m_a^2 a^2$$

overall coupling strength

relative coupling strength

ALP mass

ALP mass / couplings fixed by matching the observed DM abundance:



courtesy of R. Ziegler, based on Panci Redigolo Schwetz Ziegler '22

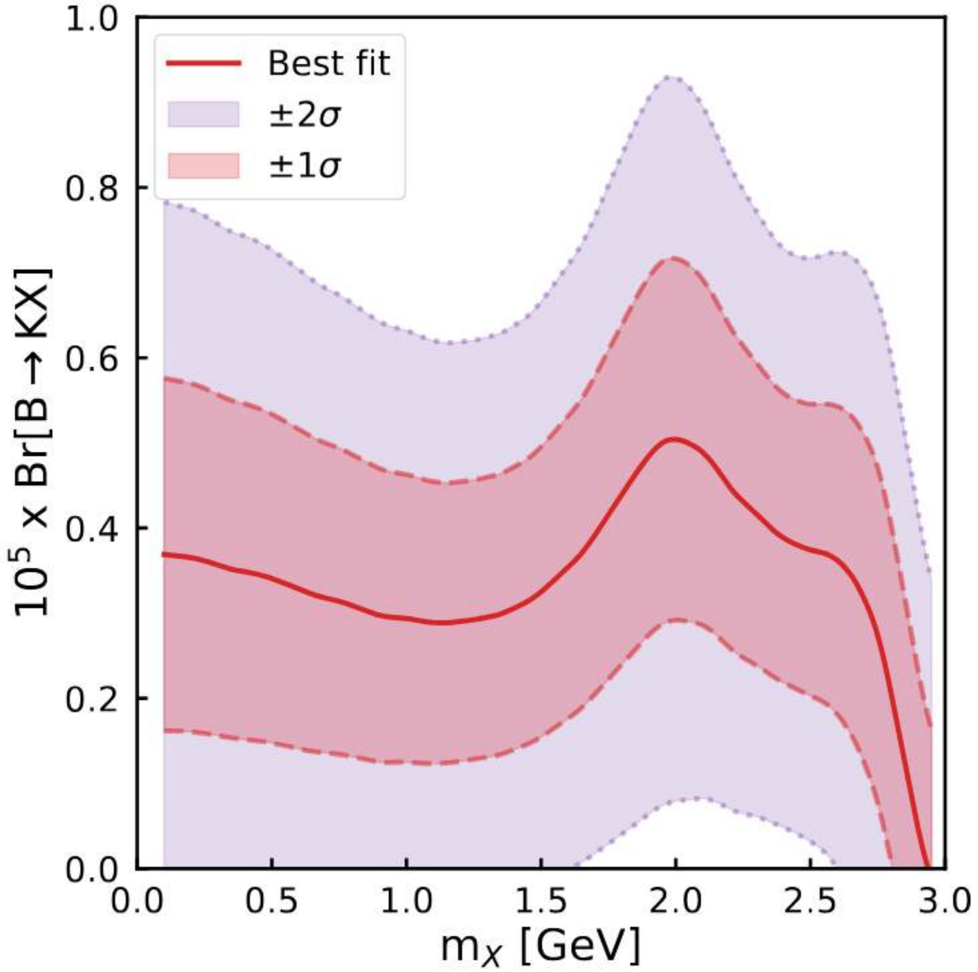
ALP portal to DM for the Belle II excess

Belle II observed a ~2.7σ excess over the SM prediction for $B^+ \to K^+ \nu\bar{\nu}$

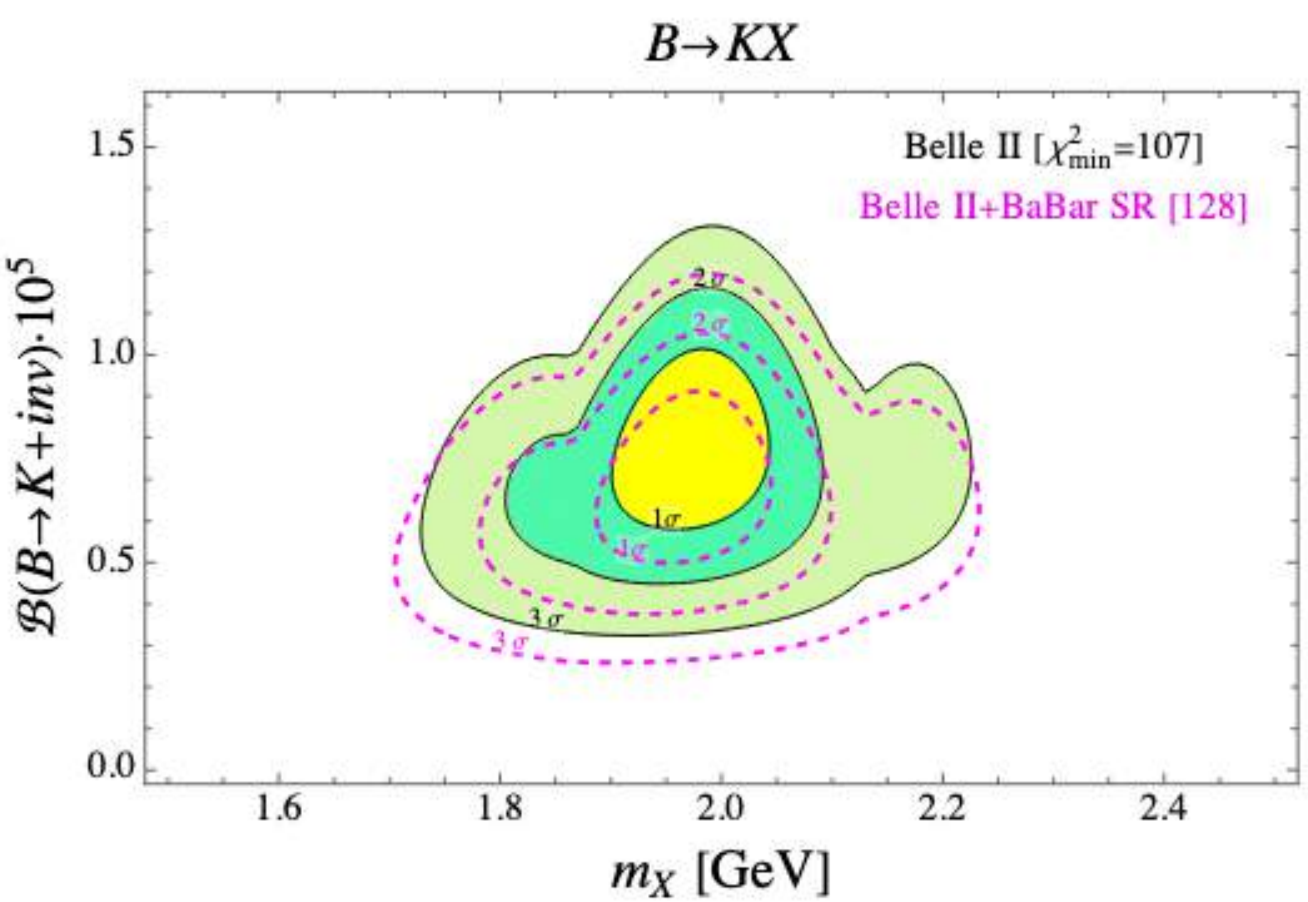
Belle II '23

→ talk by Roberta Volpe

Despite some tension with previous limits from BaBar,
the contribution of a two-body decay into an invisible ~ 2 GeV boson
is somewhat preferred to the SM alone



Altmannshofer et al. '23



Fridell et al. '23

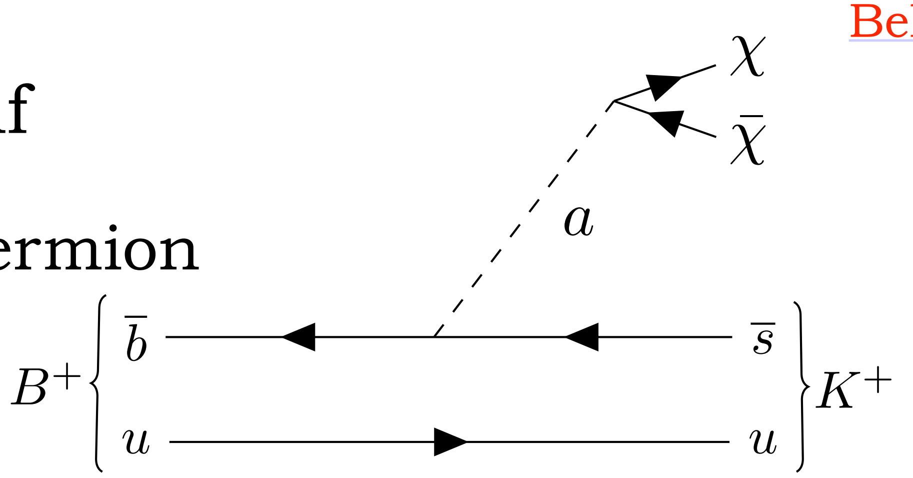
Belle II observed a ~2.7σ excess over the SM prediction for $B^+ \to K^+ \nu\bar{\nu}$

Belle II '23

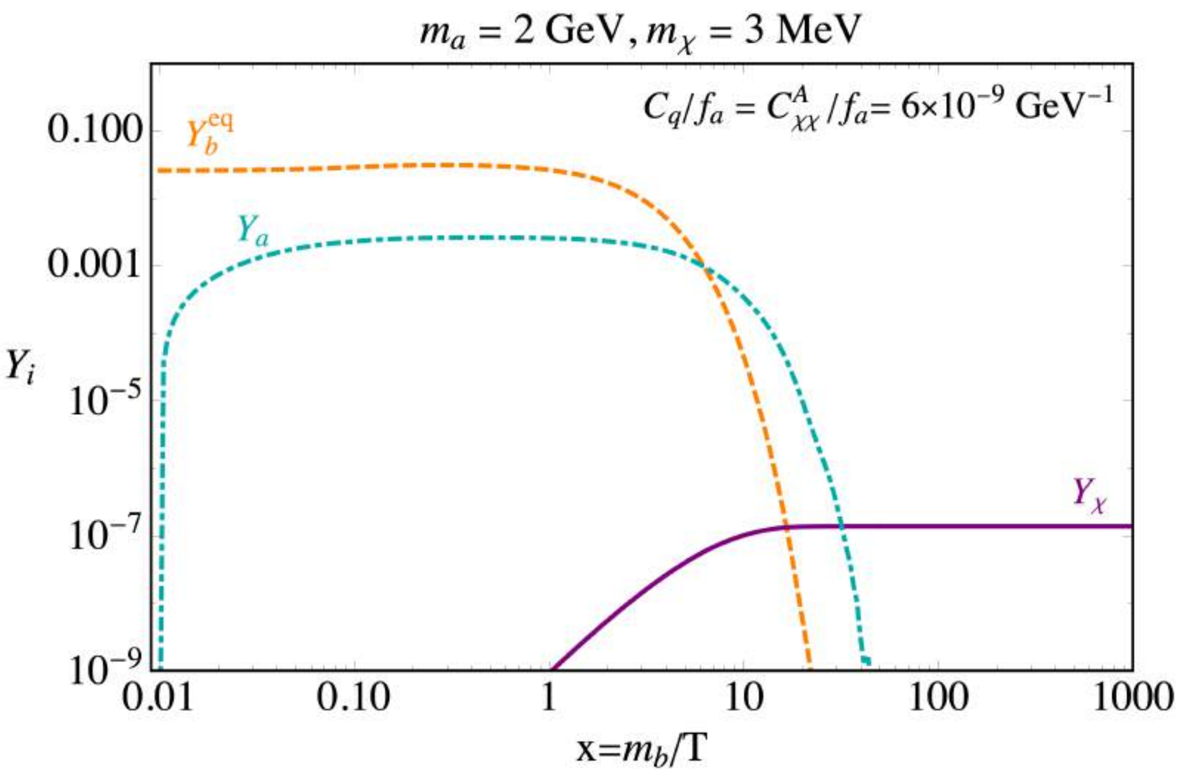
A 2 GeV ALP can not be dark matter itself but can act as portal to DM:

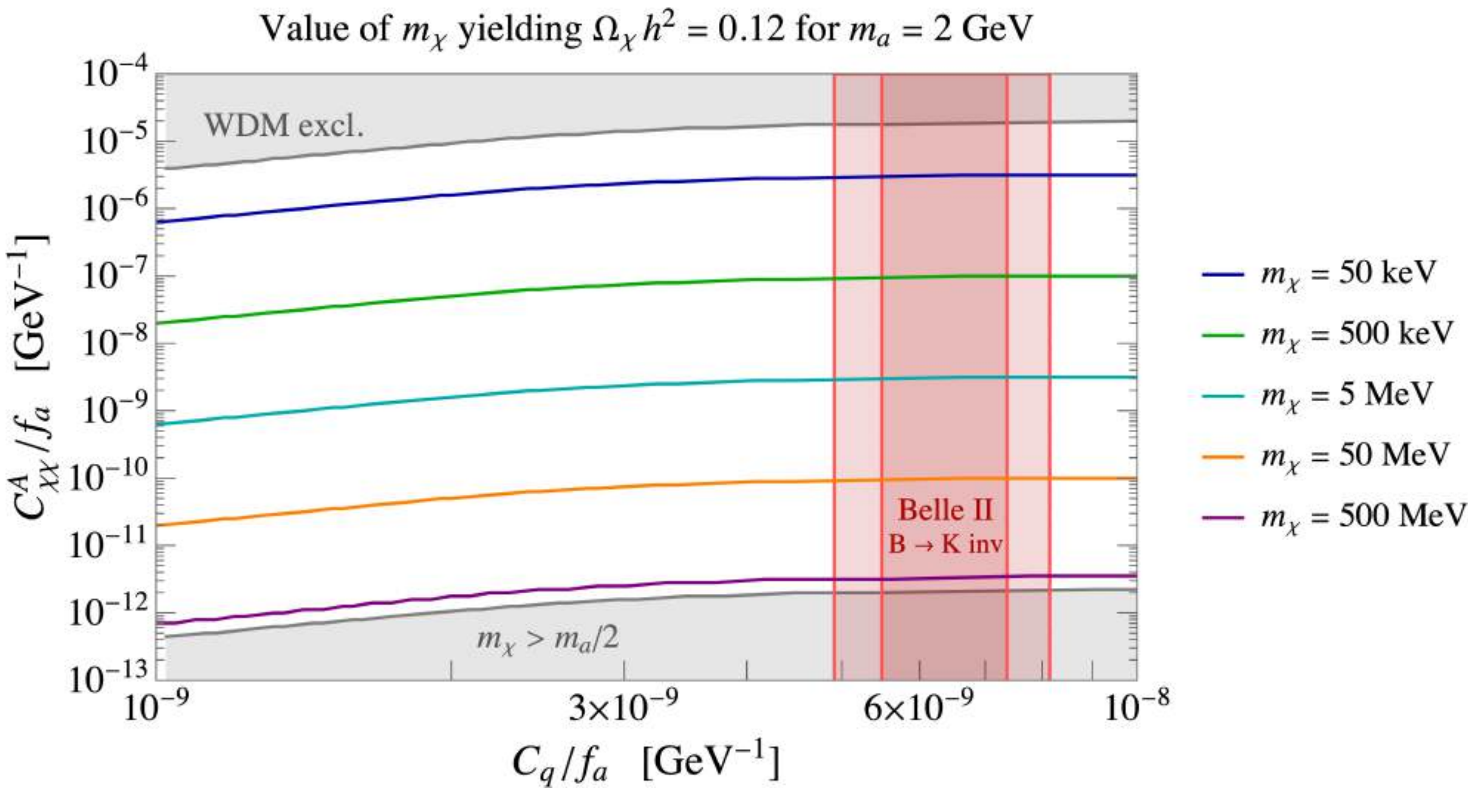
$$\mathcal{L}_{a\chi\chi} = \frac{\partial_\mu a}{2 f_a} C^A_{\chi\chi}\, \bar{\chi}\gamma^\mu\gamma_5\chi$$

dark fermion



ALP decays into light fermion DM can explain the excess at the same time yielding 100% of the observed DM abundance via freeze-in:





LC Li Mukherjee Schmidt '25

Summary

A wide class of new physics models entails light new physics with flavour-violating couplings to SM fermions

Past (upcoming) searches for muon/kaon decays into invisible ALPs can test new physics scales up to $10^{10}/10^{12}$ GeV

Interesting complementary to tau and B decays, as well as astrophysical/cosmological bounds

Models of light dark matter (accounting for 100% of the measured density) can give rise to observable signals in lepton, kaon or bottom decays

Huge room for improvement over old limits: next generation flavour experiments may discover light new physics

Cảm ơn!

Thanks!

Questions?

Additional slides

- Crystal Box 1988

PHYSICAL REVIEW D VOLUME 38, NUMBER 7 1 OCTOBER 1988

Search for rare muon decays with the Crystal Box detector

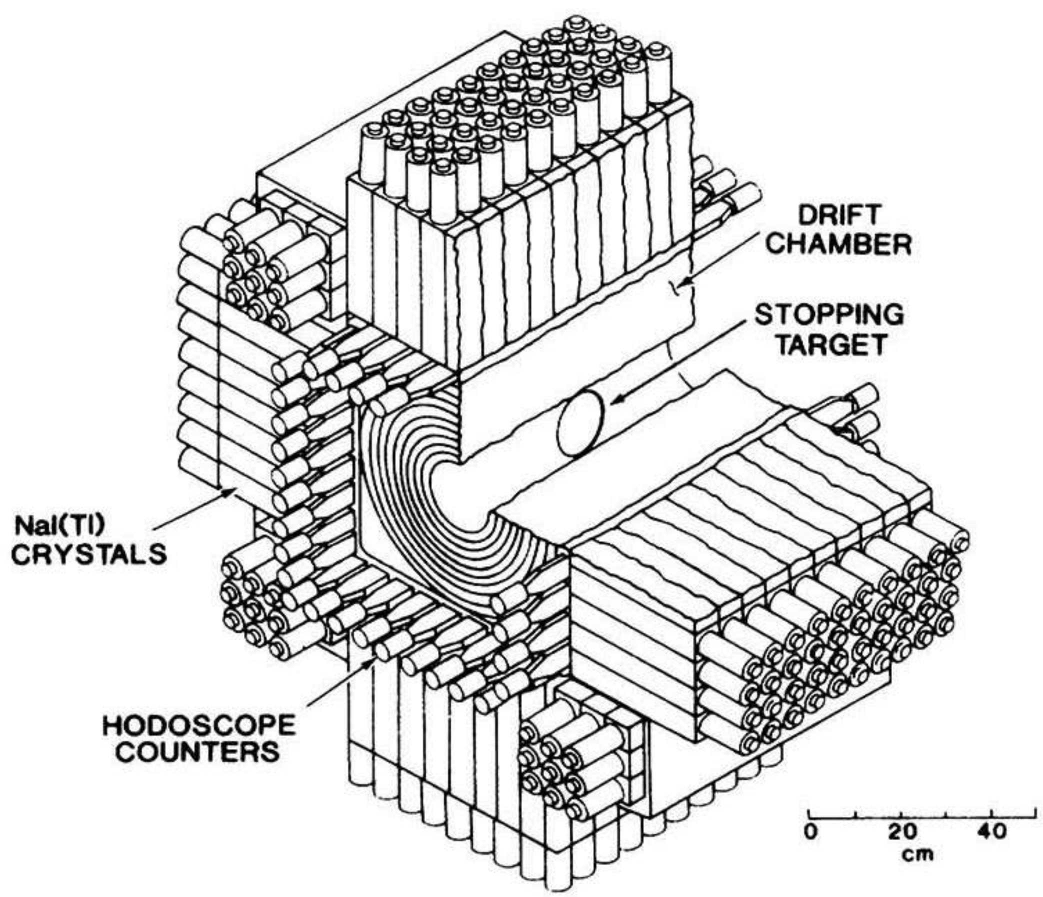


TABLE I. Types of events generated with the Monte Carlo program.

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

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

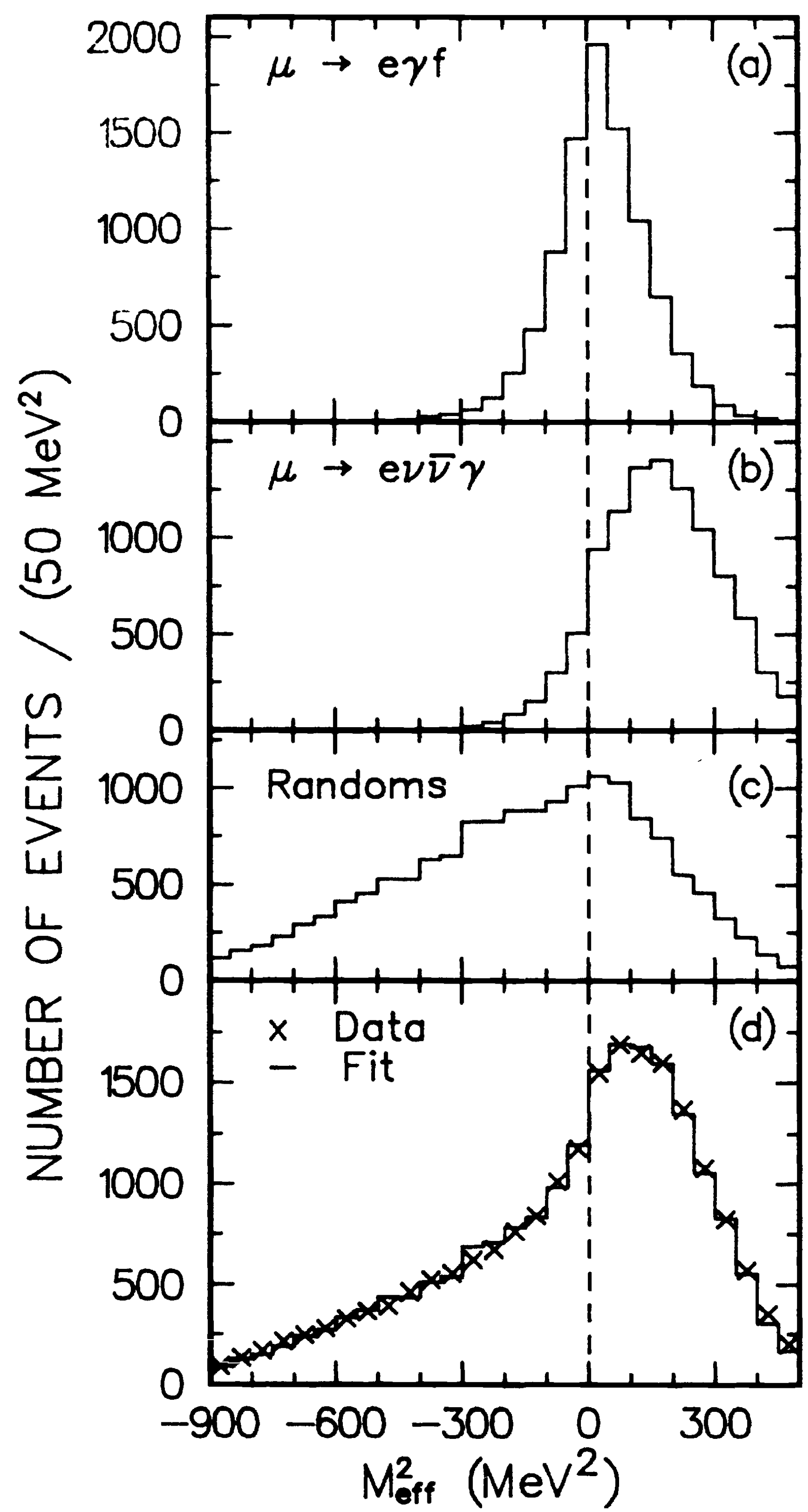
$$x = 2E_e/m_\mu \qquad y = 2E_\gamma/m_\mu$$

Crystal Box energy thresholds:

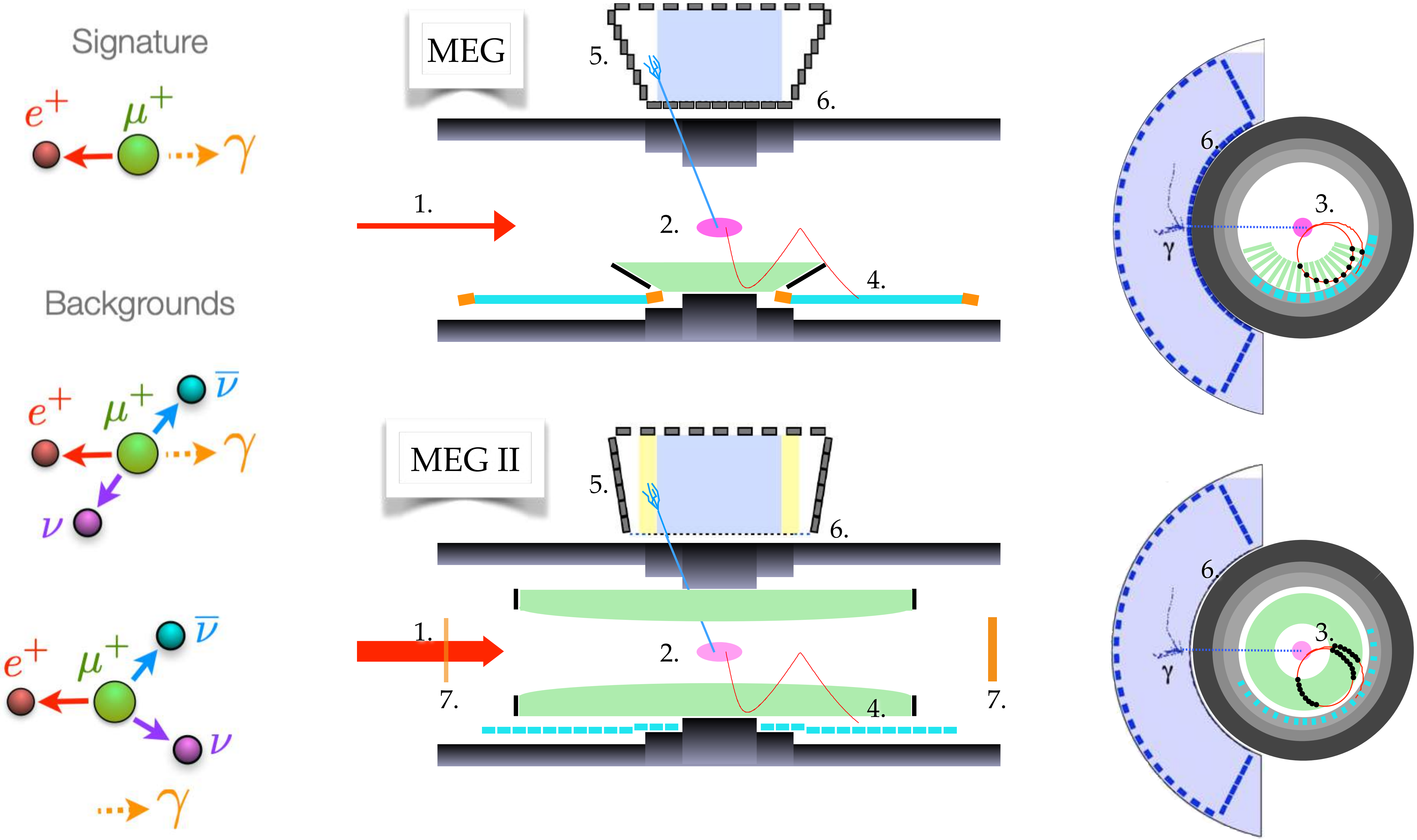
$$E_e > 38 - 43\ \mathrm{MeV}\,, \quad E_\gamma > 38\ \mathrm{MeV} \quad \Rightarrow \quad x_{\rm min} = 0.72 - 0.81\,,\ y_{\rm min} = 0.72$$

$$\Rightarrow \quad F_{e\mu} > (5.1 - 8.3) \times 10^8\ \mathrm{GeV}$$

weaker but independent of V/A nature of the couplings



Future prospects: MEG II

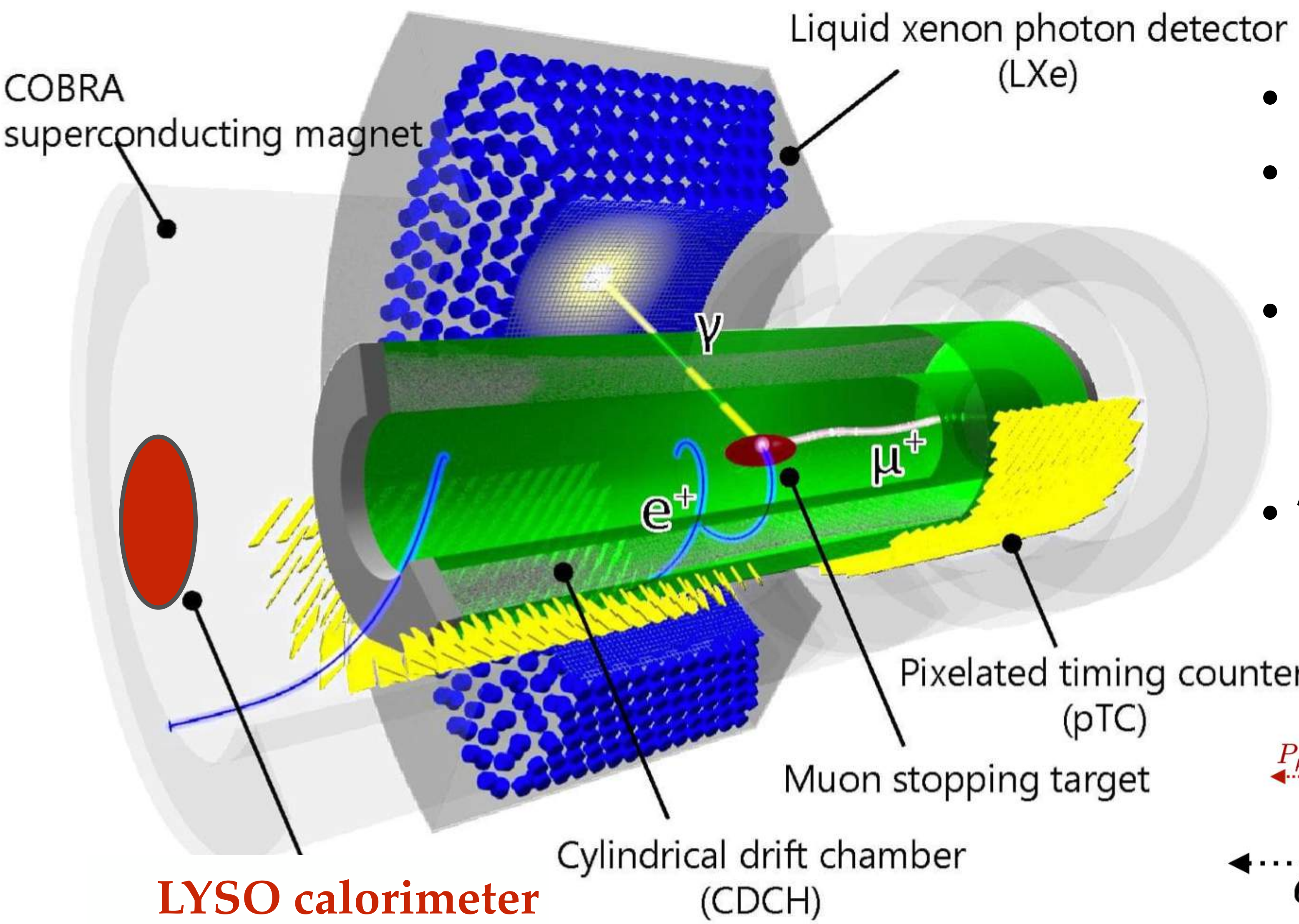


LC Redigolo Ziegler Zupan '20

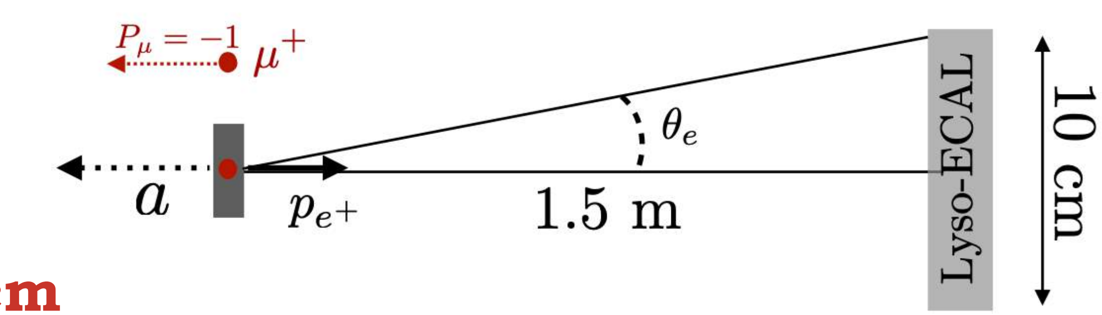
- Prospect at MEG II for $\mu \to e\, a$

What about a Jodidio-like search at MEG II for $m_a \approx 0$ with a *forward calorimeter*?
We propose a modified setup of MEG II ("MEGII-fwd") and ~2 weeks dedicated run

idea from discussions with A. Papa and G. Signorelli, thanks!



- Muon beam already polarized
- A suitable magnetic field can reduce depolarization effects
- Reconfiguring the field we can also increase the acceptance ("*magnetic focusing*" up to F~100)
- Two weeks of run after MEG II main run are enough to improve the bound (even with F=0)



LYSO calorimeter

~1.5 m from the target, diameter ~ 10 cm

Future prospects: MEG II

- Prospect at MEG II for $\mu \to e\, a$

LC Redigolo Ziegler Zupan '20

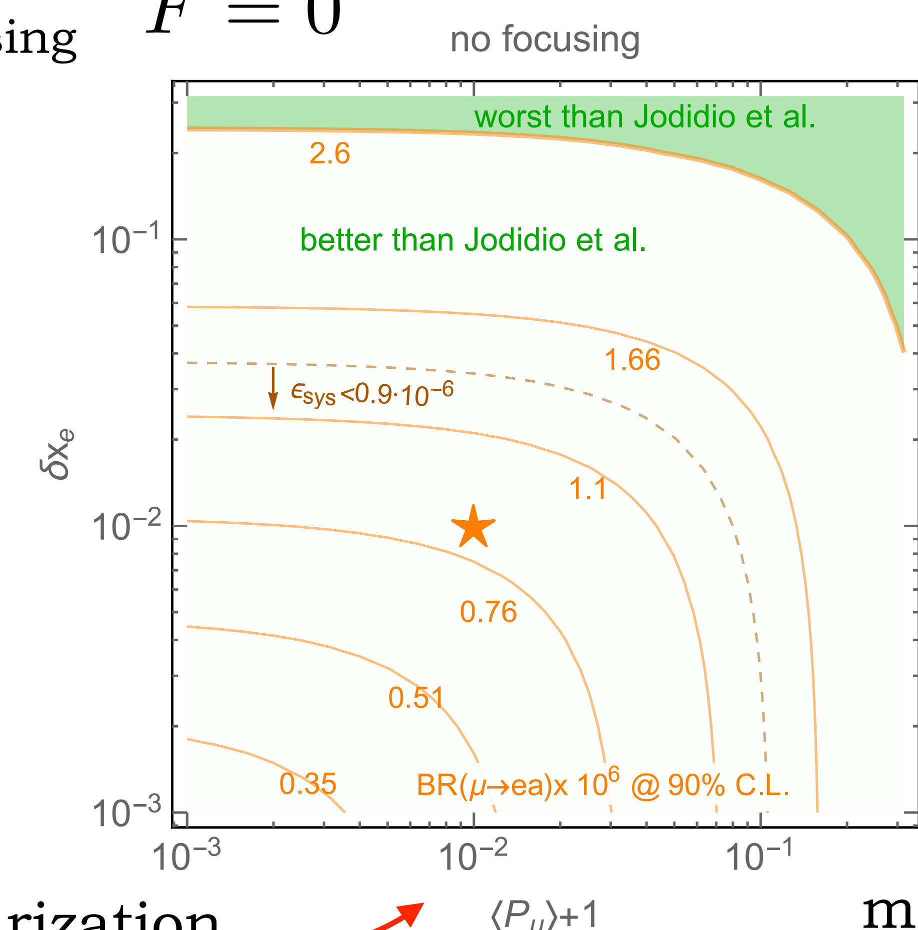
What about a Jodidio-like search at MEG II for $m_a \approx 0$ with a *forward calorimeter*?
We propose a modified setup of MEG II ("MEGII-fwd") and ~2 weeks dedicated run

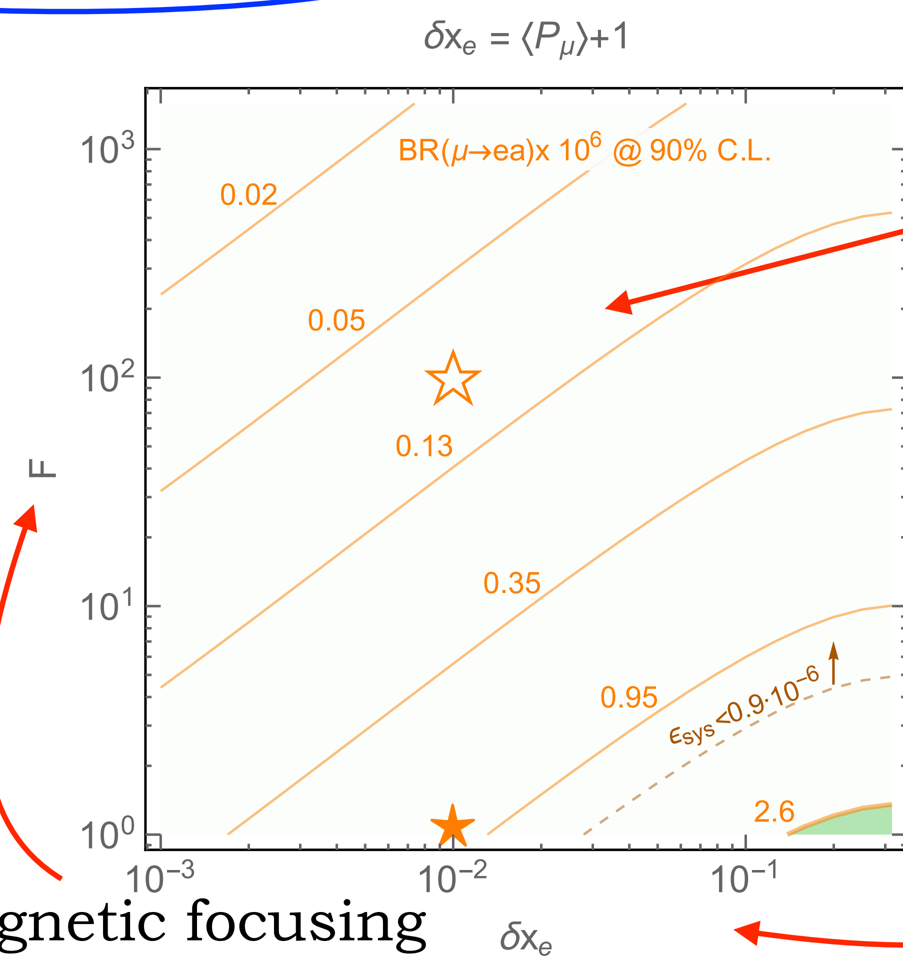
idea from discussions with A. Papa and G. Signorelli, thanks!

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

$$\text{MEGII-fwd}: \ 10^{14} \mu^+$$

magnetic focusing $F = 0$





$F = 100$
$\text{BR} \sim 10^{-7}$

Positron momentum resolution

$$x_e = \frac{2p_e}{m_\mu}$$

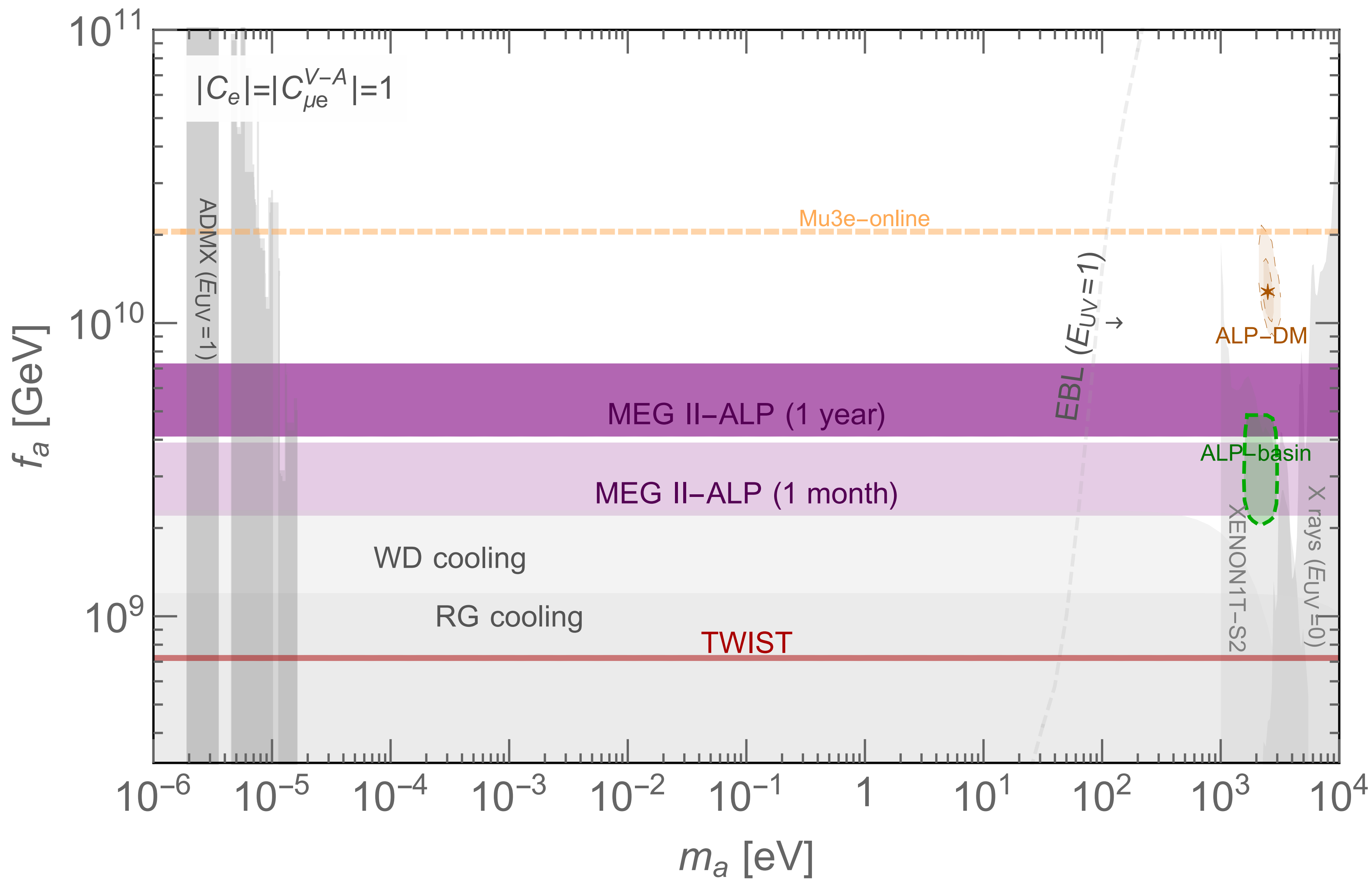
polarization

magnetic focusing

- Prospect at MEG II for $\mu \to e\, a\, \gamma$

Jho Knapen Redigolo '22

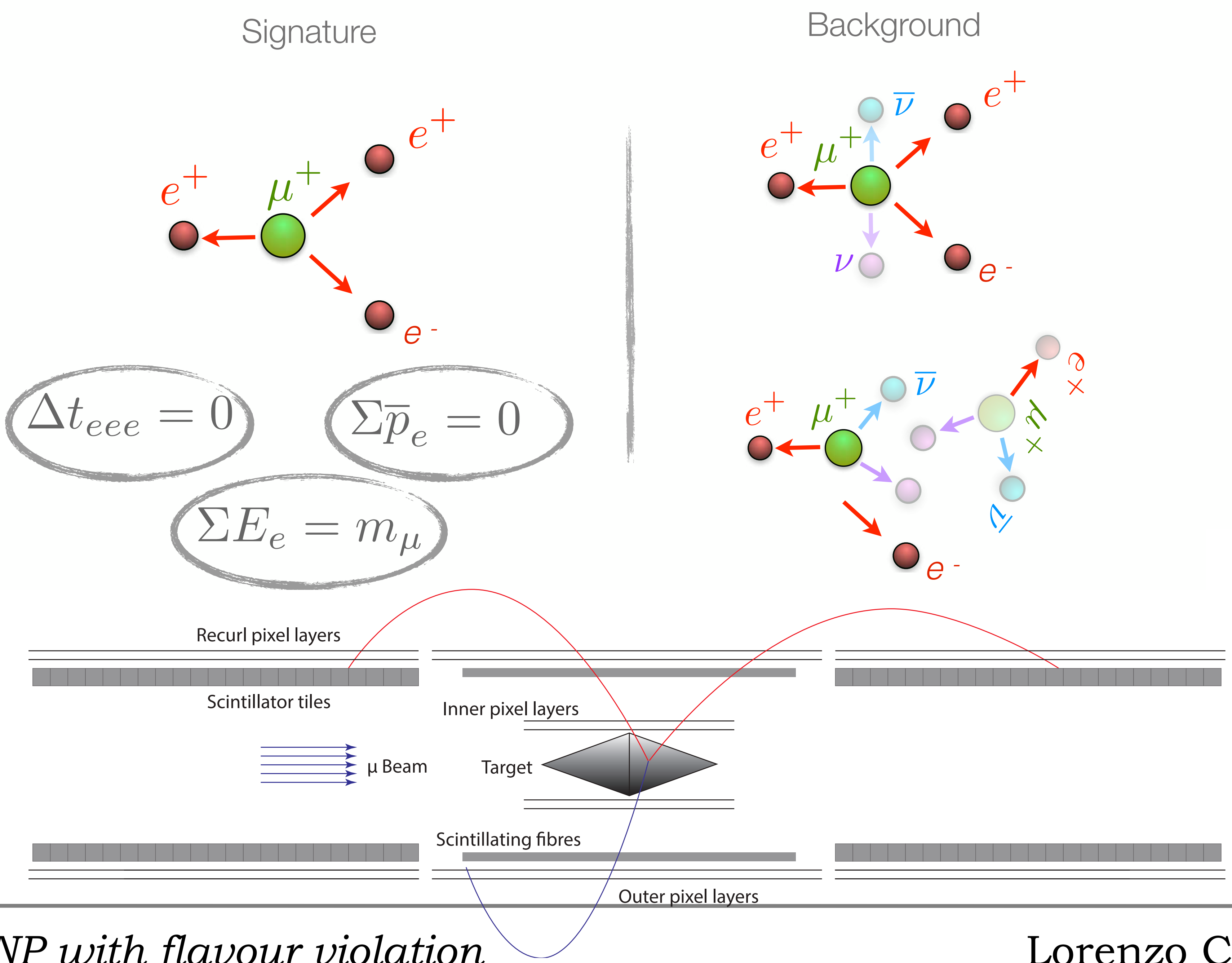
Search sensitive to V-A couplings too, requires a dedicated trigger:



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

slide borrowed from A. Papa

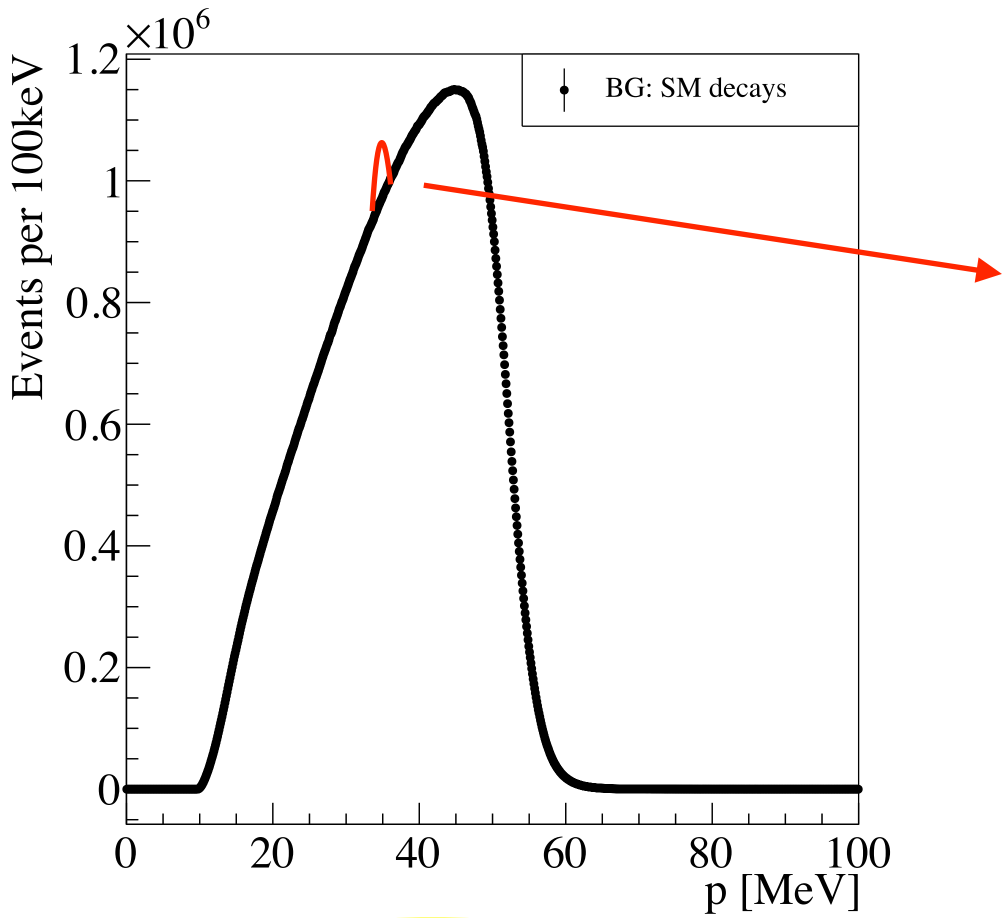
- The Mu3e experiment aims to search for $\mu^+ \to e^+ e^+ e^-$ with a sensitivity of ~10^{-15} (Phase I) up to down ~10^{-16} (Phase II). Previous upper limit $BR(\mu^+ \to e^+ e^+ e^-) \leq 1 \times 10^{-12}$ @90 C.L. by SINDRUM experiment)
- Observables (E_e, t_e, vertex) to characterize $\mu \to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



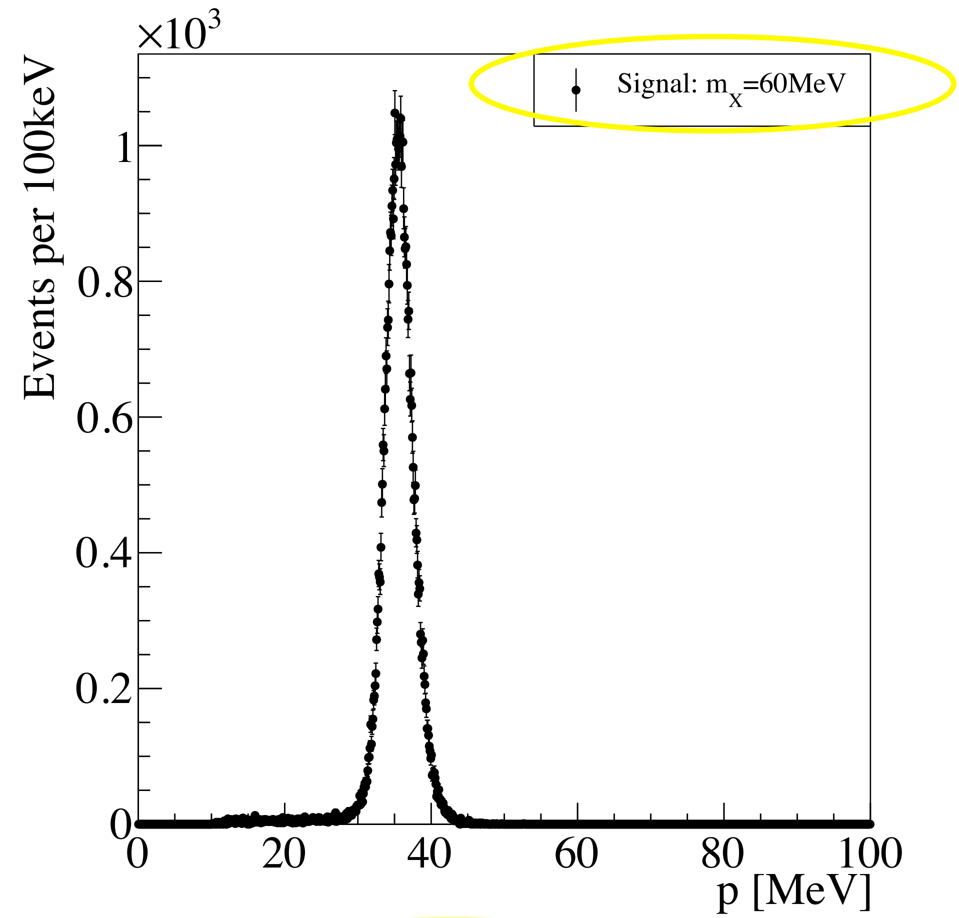
Perrevoort (Mu3e) '18

- Mu3e prospect for $\mu \to e\, a$

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



(a) Simulated background events.



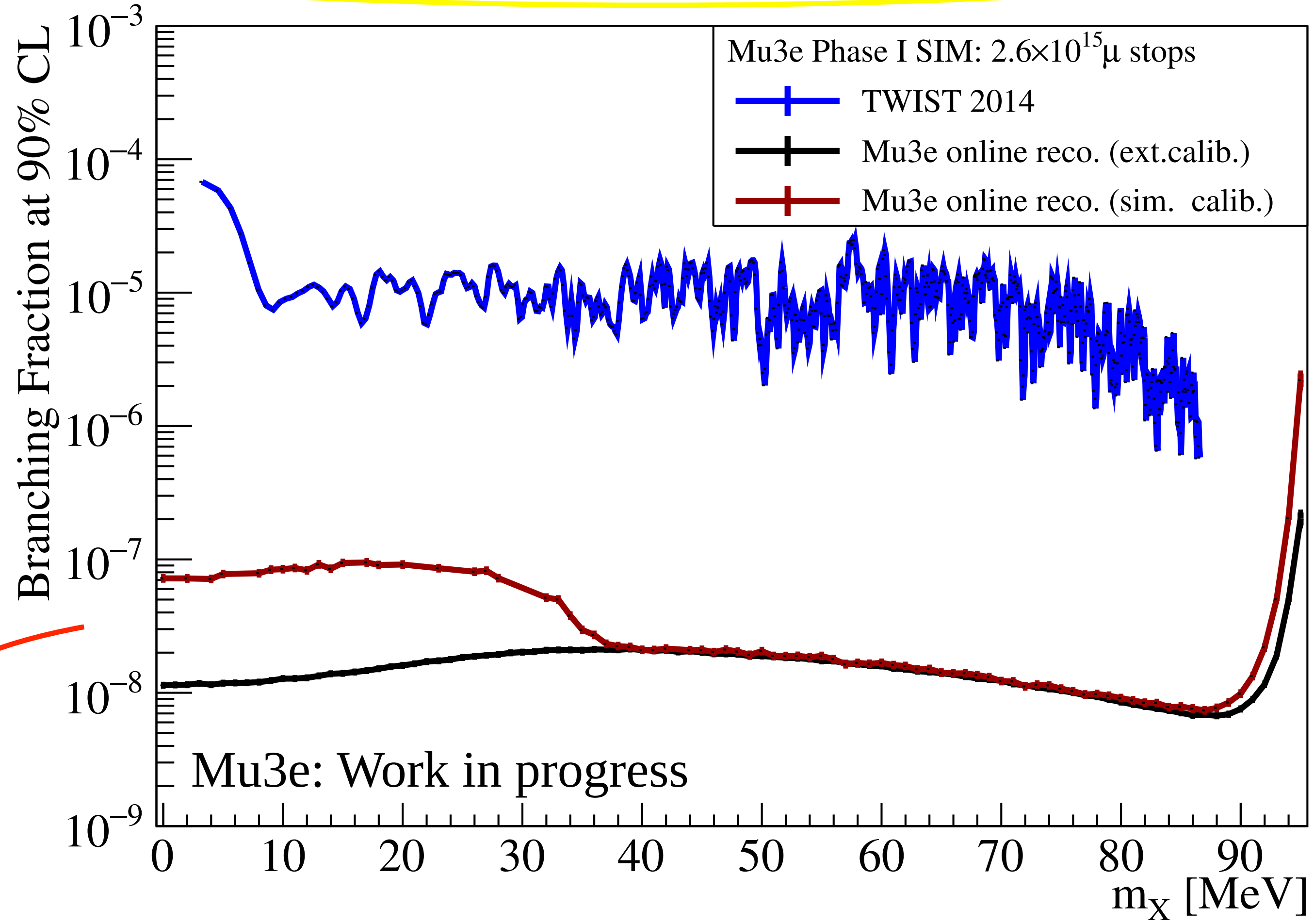
(b) Simulated $\mu \to eX$ signal events.

- Mu3e prospect for $\mu \to e\, a$

Perrevoort (Mu3e) '18

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

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

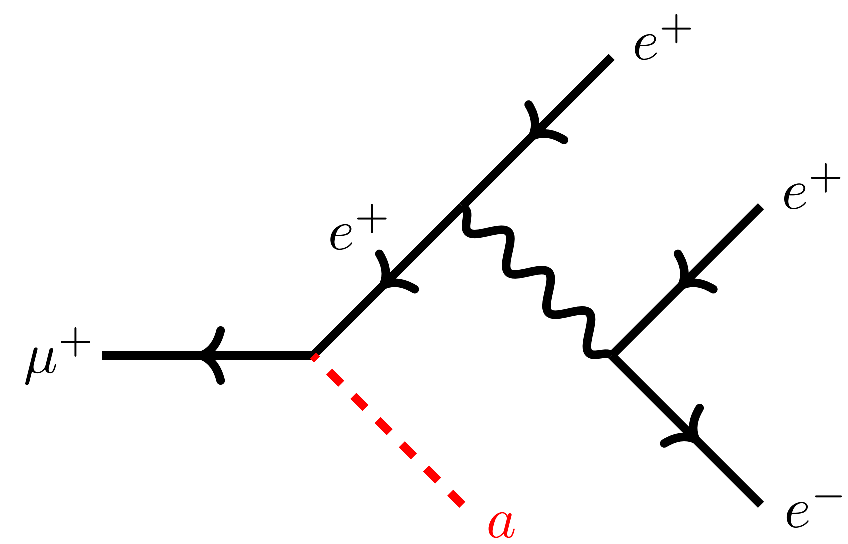


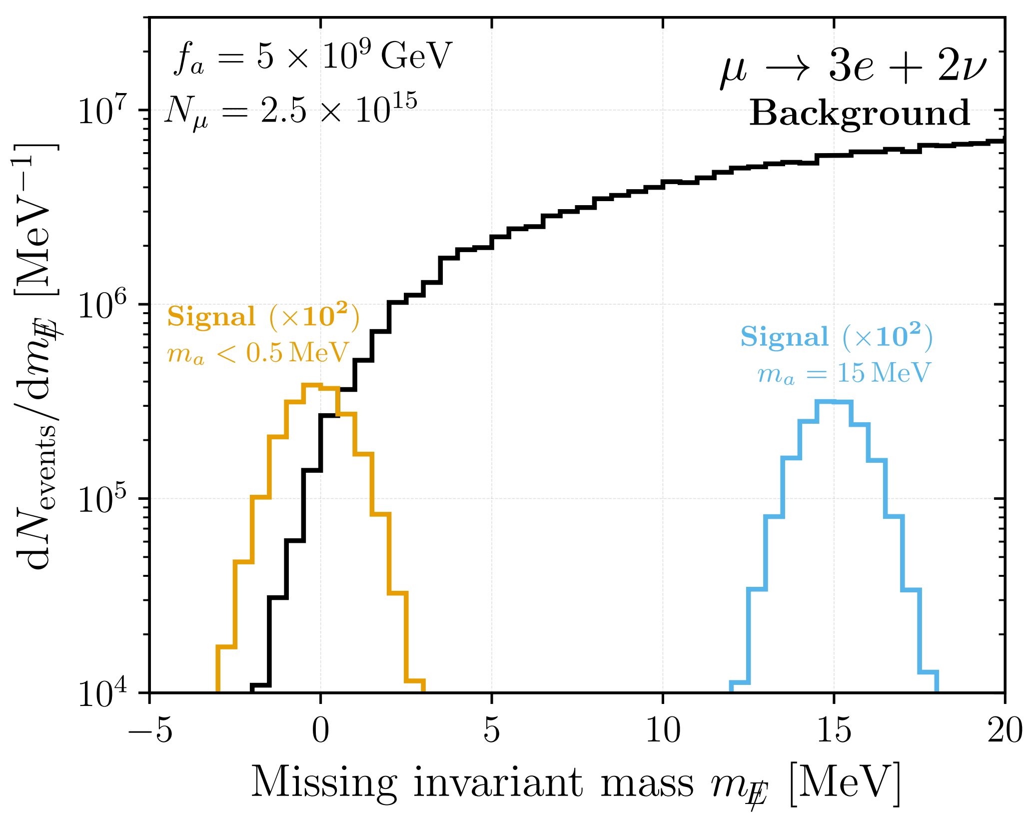
$$m_a \approx 0 \;:\quad \mathrm{BR}(\mu \to e a) < 7 \times 10^{-8} \quad \Rightarrow \quad F_{\mu e} \gtrsim 3 \times 10^{10}\ \mathrm{GeV}$$

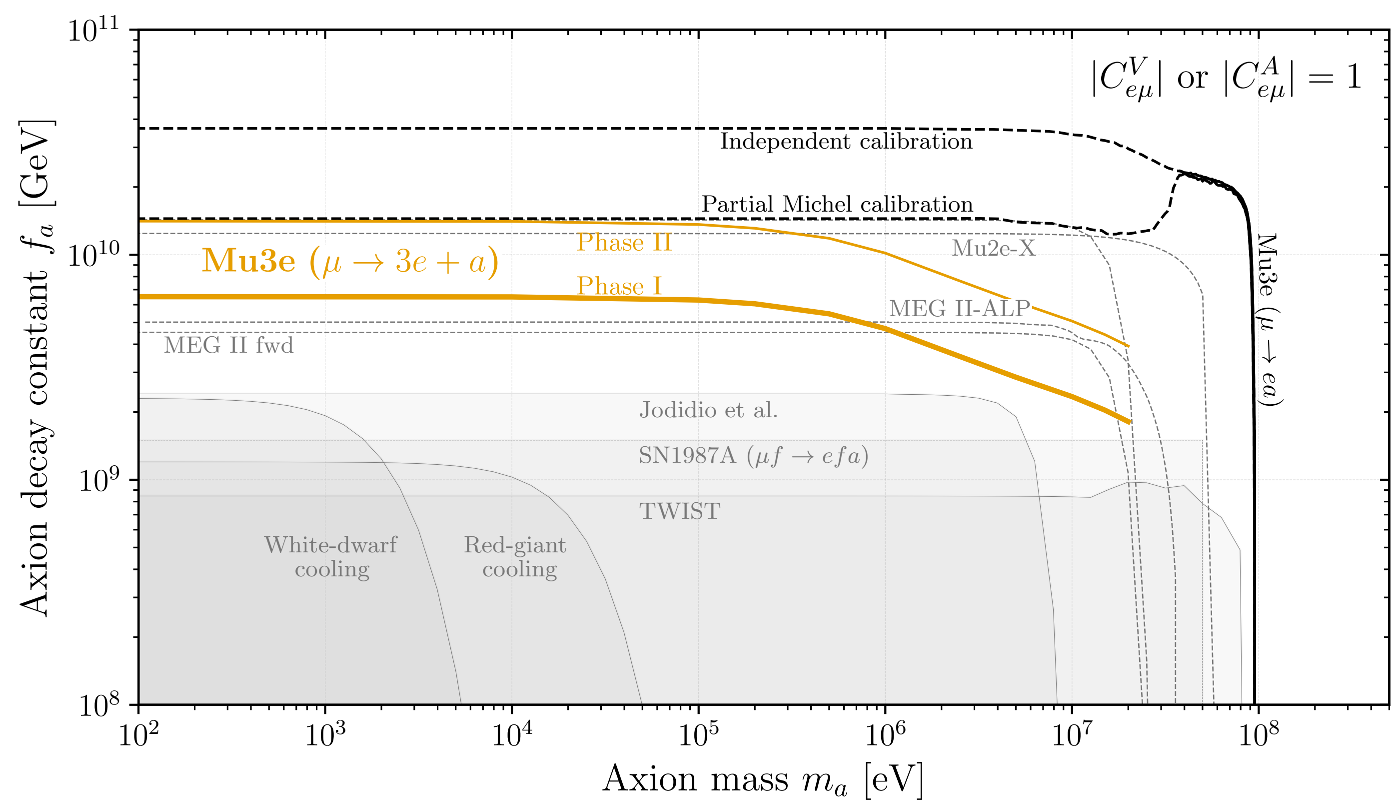
- Mu3e prospect for $\mu \to 3e\, a$

Knapen Langhoff Opferkuch Redigolo '23

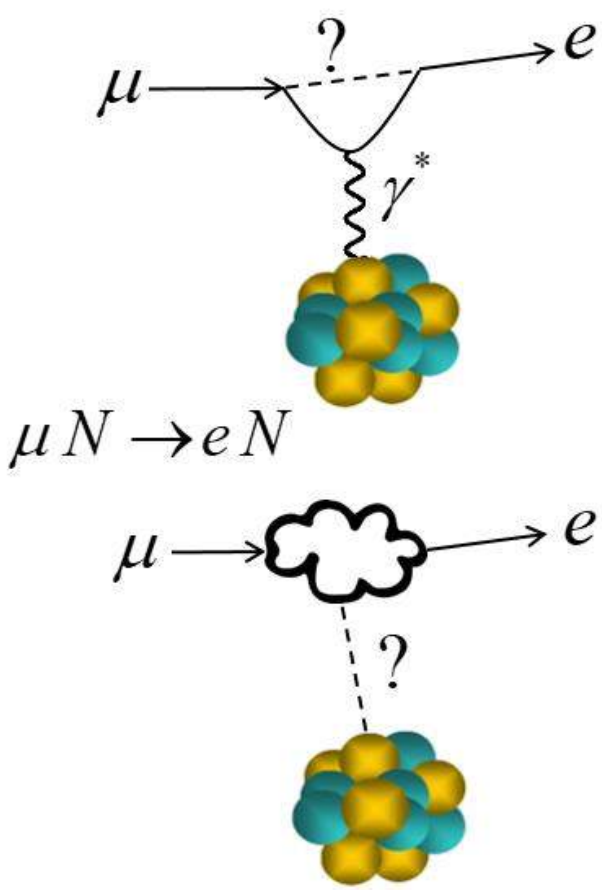
Search for $3e$ + invisible from the internal conversion of virtual photon into a e^+e^- pair:

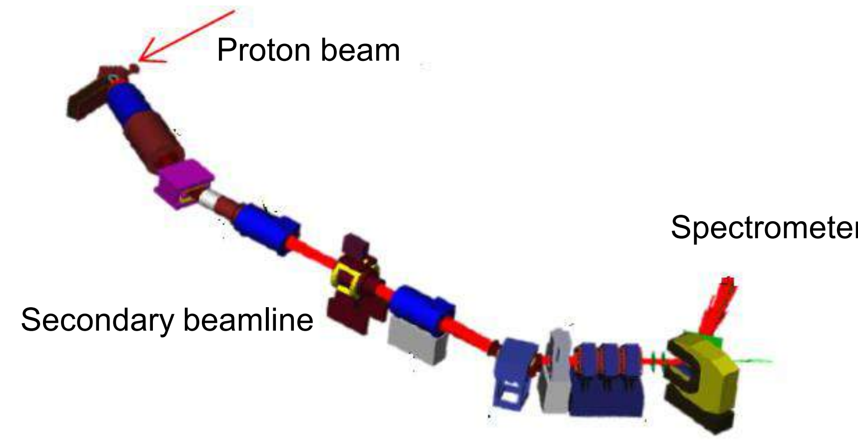


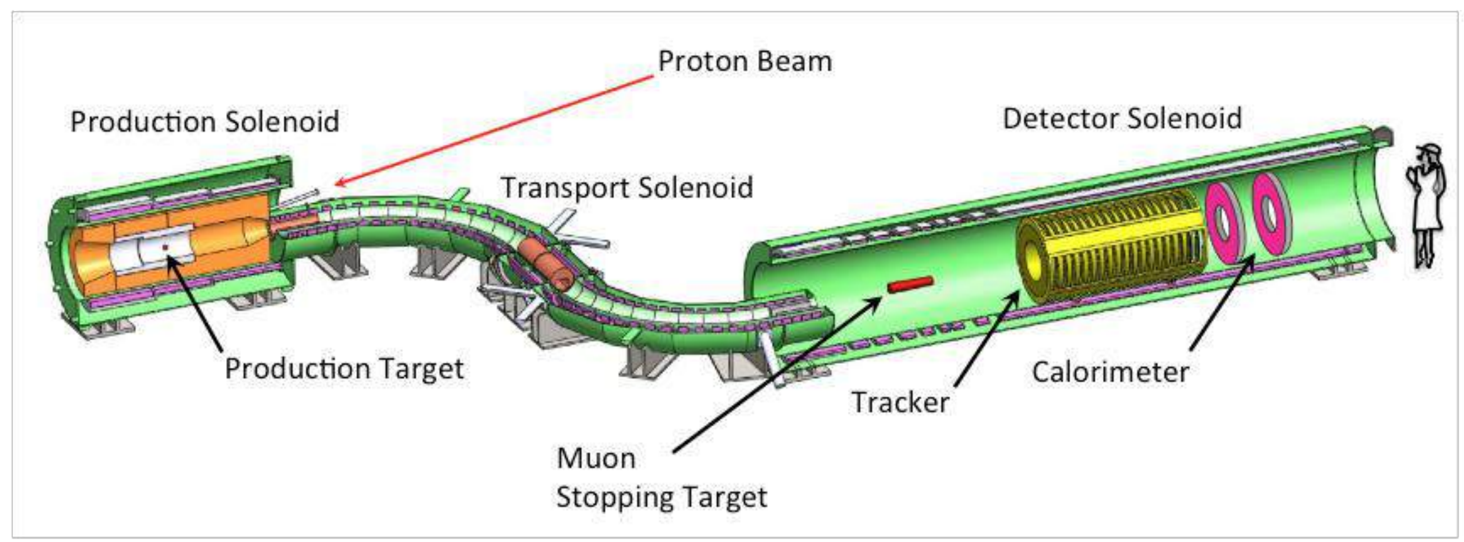




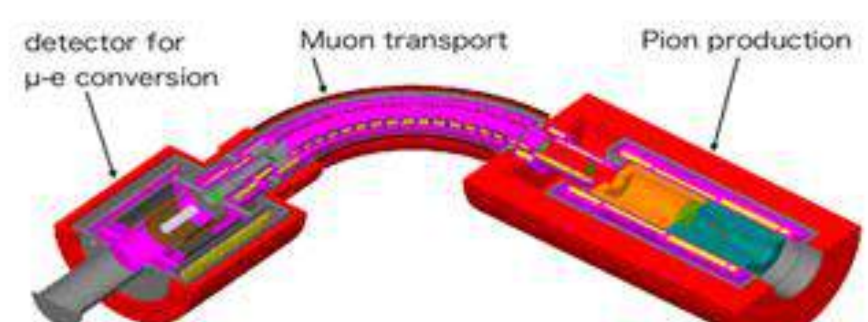
$\mu \to e$ conversion in nuclei experiments







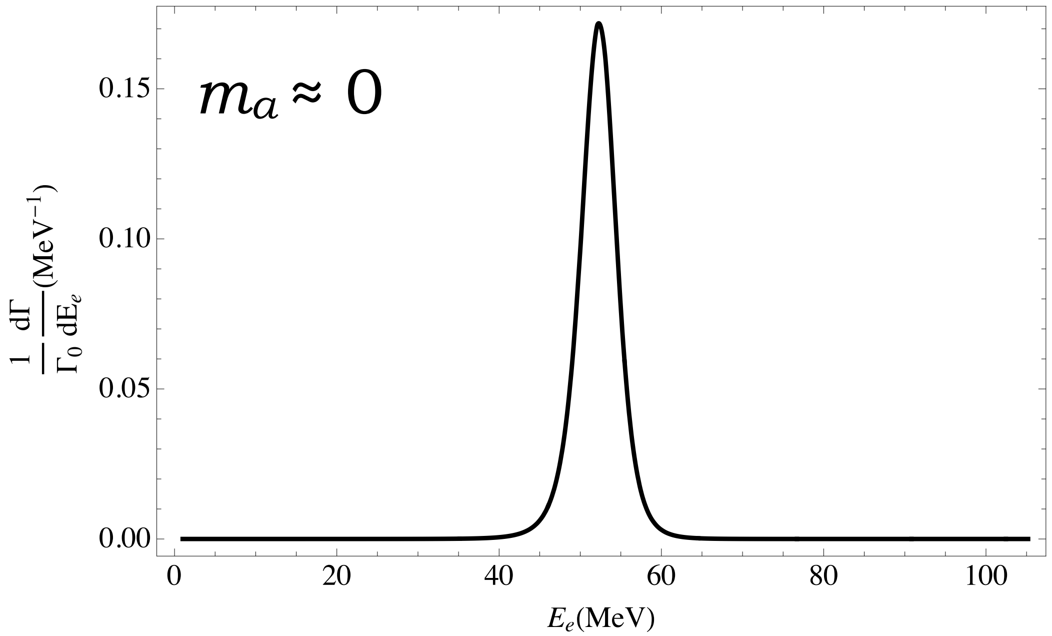
David Hitlin
Beijing CLFV School
June 3-7, 2019
Lecture 1

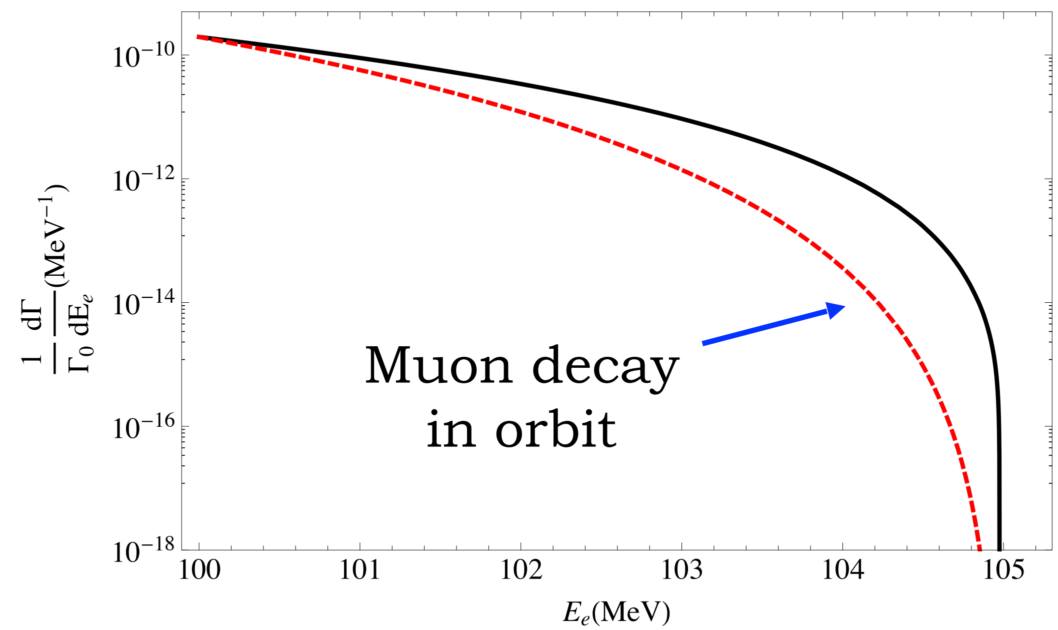


- Prospect at $\mu \to e$ conversion experiments

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:

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

- N_R: Phase-space correction factor
- $\Gamma_{\text{capture}}/\Gamma(\mu \to e\nu_\mu\bar{\nu}_e)$: 27 (in Al)
- $R_{\mu e}$: 10^{-17}
- f_J: Fraction of $\mu \to ea$ events in the signal region: 2×10^{-10} (E_e > 100 MeV)

Possible bound at the level of Jodidio et al.

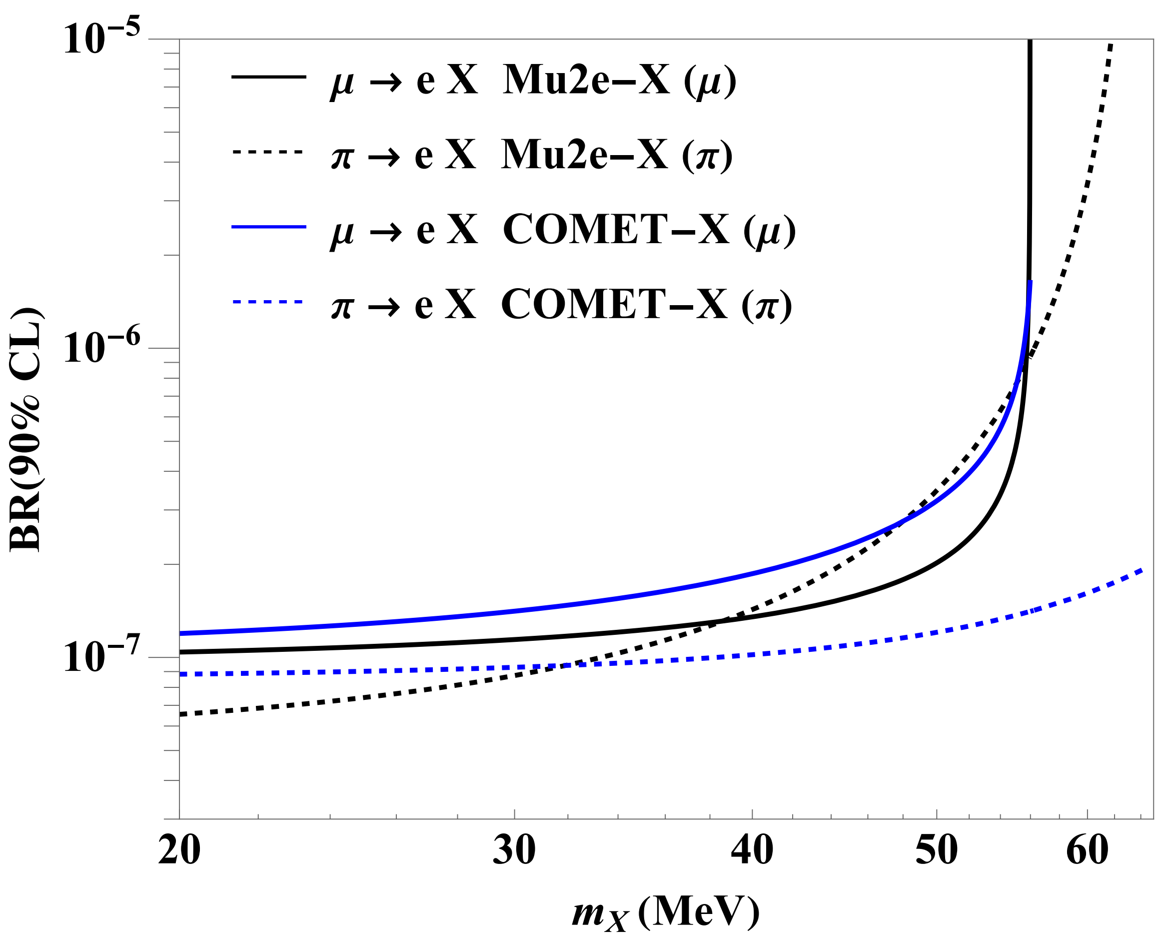
Limited by the $\mu \to e$ conv. signal region (only the tail included): dedicated search?

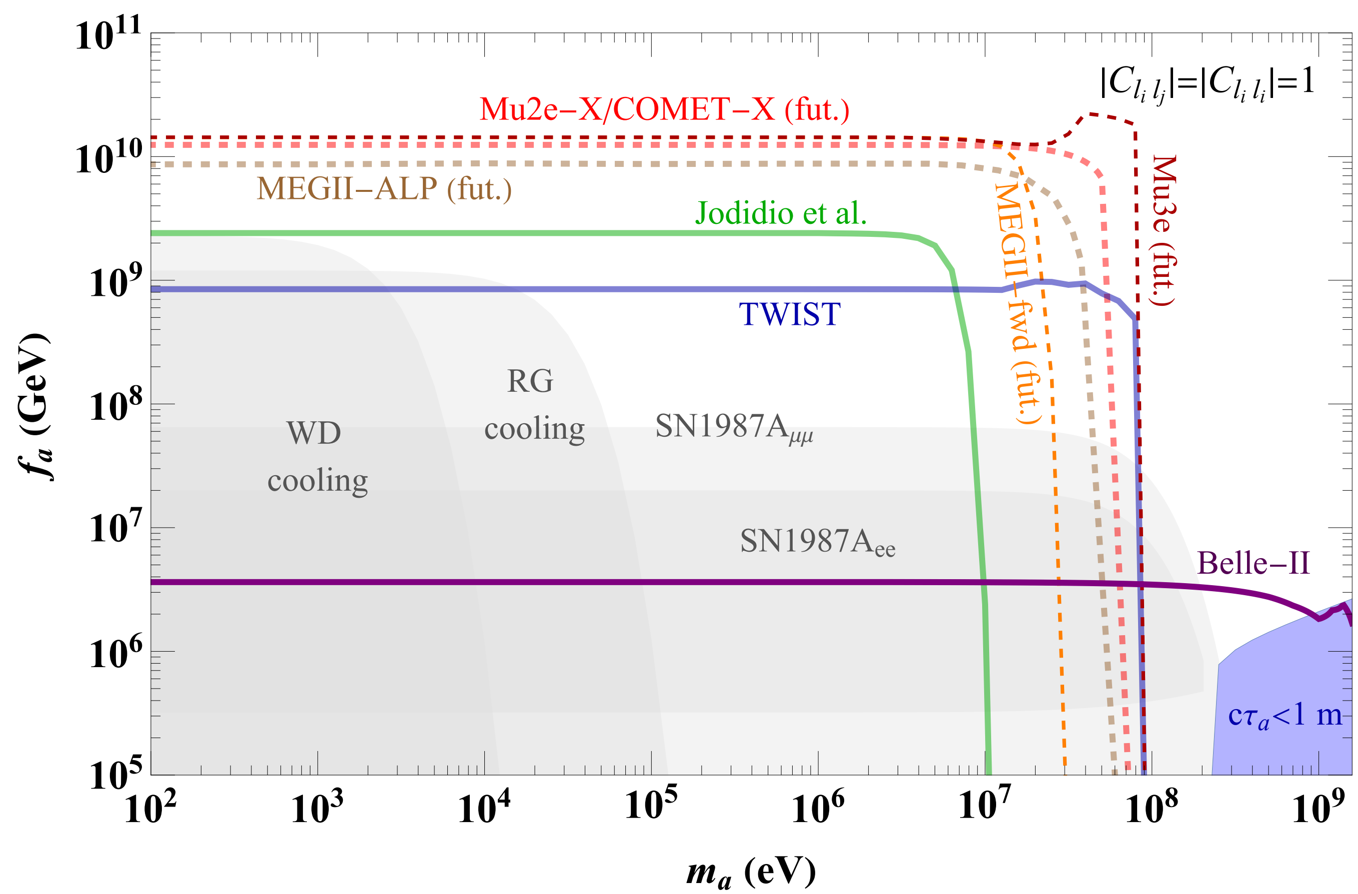
- Prospect at $\mu \to e$ conversion experiments

Hill Plestid Zupan '23

Conversion experiments employ μ^- beams to form muonic atoms: in the signal window for $\mu \to e$ conversion, the SM bg is suppressed, but $\mu \to ea$ would be too

Idea: search for a mono-energetic positron excess over the Michel spectrum, using data from calibration runs employing *positive* muon beams (10^{13} - $10^{14}\mu^+$)





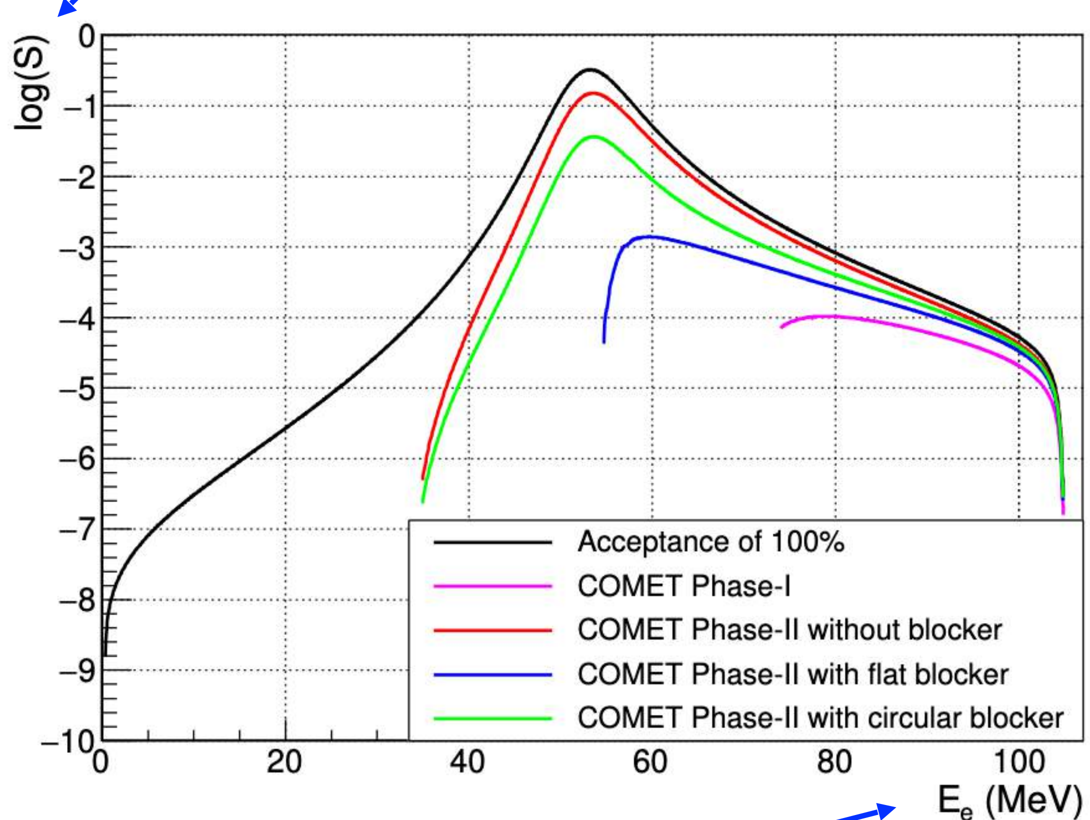
Future prospects for ALP searches: a COMET study

- Prospect at $\mu \to e$ conversion experiments

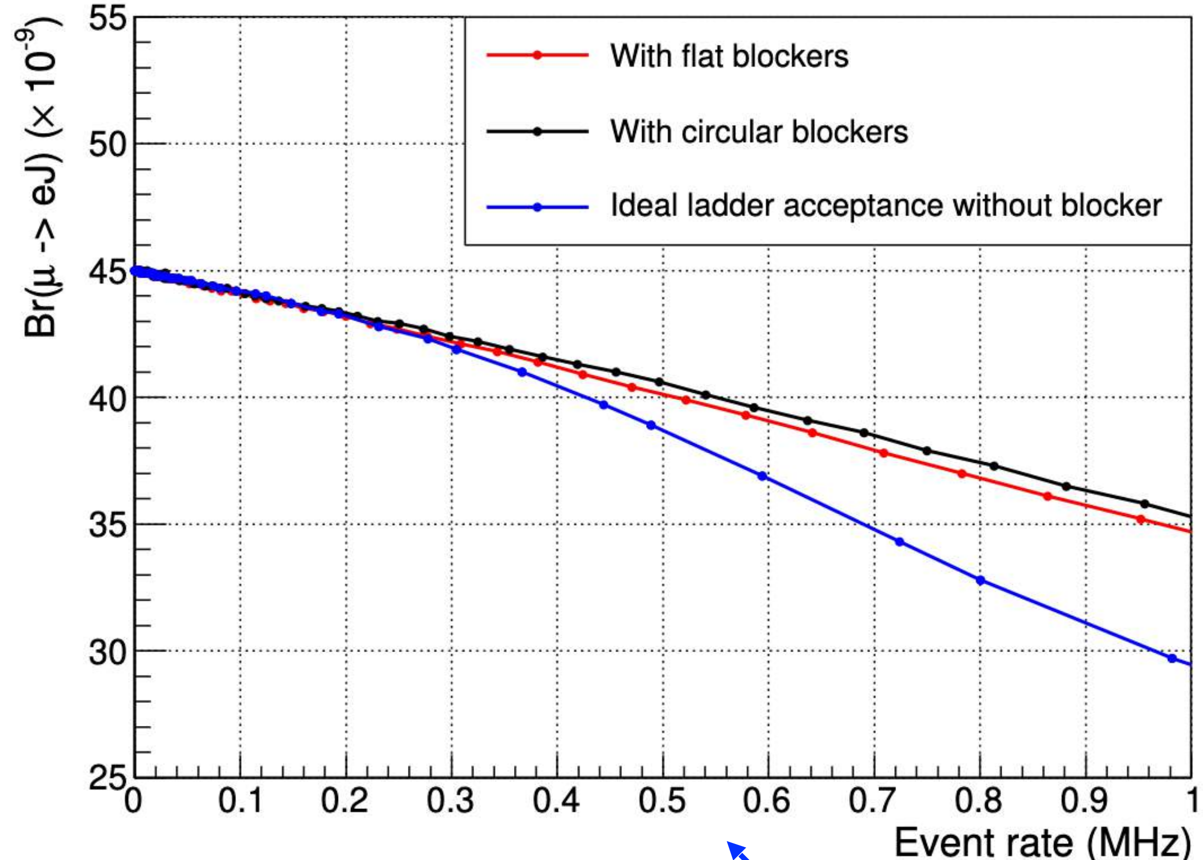
Xing et al. '22

One can try to lower the lower limit of the signal window
(very large background from muons decaying in orbit)

Significance factor



lower limit of
signal window



⇨ COMET Phase II can reach ~10^{-8} coping with a bg rate ~O(100)kHz

If muons can not decay to on-shell ALPs (i.e. $m_a > m_\mu$), constraints on LFV ALPs are much weaker

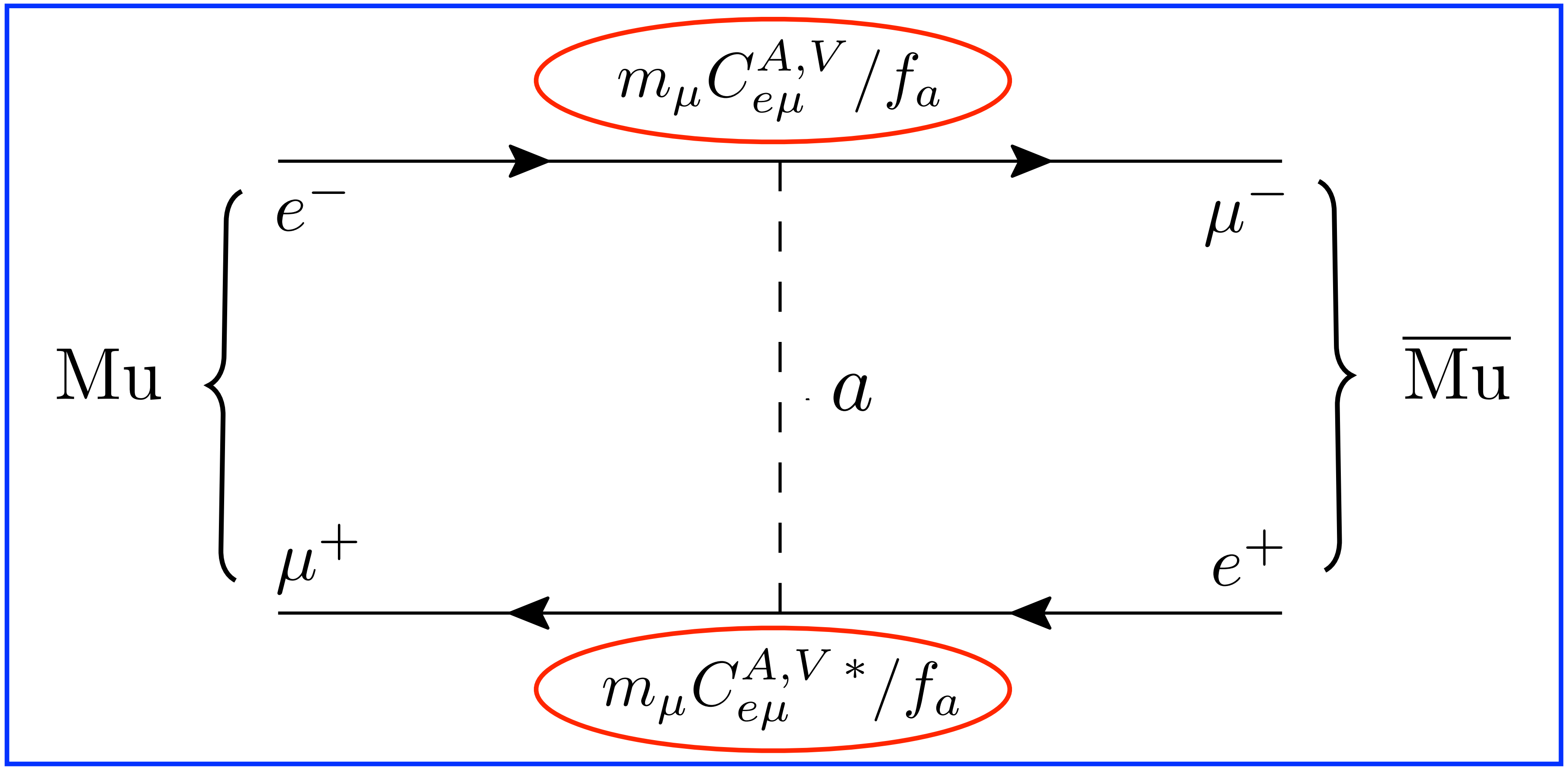
We have two possible strategies to test the μ-e interaction:

Indirect tests through processes they induce:
e.g. *muonium-antimuonium conversion*

Direct production in muon beam collisions,
e.g. $\mu^+ e^- \to a\, \gamma$ at the proposed μTRISTAN project

Hamada et al. '22

Low-energy test: muonium to antimuonium conversion



$$P_{\mathrm{Mu}\,\overline{\mathrm{Mu}}} = \frac{m_\mu^4}{2\pi^2 a_B^6 \Gamma_\mu^2 [(m_\mu^2 - m_a^2)^2 + \Gamma_a^2 m_a^2] f_a^4} \left[|c_{0,0}|^2 \left| (C_{e\mu}^V)^2 - \left(1 + \frac{1}{\sqrt{1+X^2}}\right) (C_{e\mu}^A)^2 \right|^2 + |c_{1,0}|^2 \left| (C_{e\mu}^V)^2 - \left(1 - \frac{1}{\sqrt{1+X^2}}\right) (C_{e\mu}^A)^2 \right|^2 \right],$$

Limits on the conversion probability:

Present: $P_{\mathrm{Mu}\,\overline{\mathrm{Mu}}} < 8.3 \times 10^{-11}$ MACS '98

x1000 improvement

Future: $P_{\mathrm{Mu}\,\overline{\mathrm{Mu}}} < 7 \times 10^{-14}$ MACE '24

High-energy option: the μTRISTAN proposal

μTRISTAN proposal : $\mu^+\mu^+$ and μ^+e^- colliders

PTEP
Prog. Theor. Exp. Phys. 2022 053B02(16 pages)
DOI: 10.1093/ptep/ptac059

μTRISTAN

Yu Hamada[1], Ryuichiro Kitano[1,2], Ryutaro Matsudo[1], Hiromasa Takaura[1,*], and Mitsuhiro Yoshida[2,3]
[1]*KEK Theory Center, Tsukuba 305-0801, Japan*
[2]*Graduate University for Advanced Studies (Sokendai), Tsukuba 305-0801, Japan*
[3]*KEK Accelerator Department, Tsukuba 305-0801, Japan*
*E-mail: takaura.phys@gmail.com

Received January 21, 2022; Revised March 18, 2022; Accepted March 28, 2022; Published March 30, 2022

Hamada et al. '22

- The idea is to cool and focus μ^+ beams, a technology developed at JPARC [Abe et al., 1901.03047]
- The μ^+ beams could be accelerated up to 1 TeV and made to collide with :

30 GeV e^- beam

→ "Higgs factory" with $\sqrt{s} \simeq 346$ GeV

→ Expected integrated luminosity $\mathcal{L} = 1$ ab^{-1}

OR

1 TeV μ^+ beam

→ "Discovery machine" with $\sqrt{s} = 2$ TeV

→ Expected integrated luminosity $\mathcal{L} = 100$ fb^{-1}

slide borrowed from L. Mukherjee

μTRISTAN proposal : $\mu^+\mu^+$ and μ^+e^- colliders

PTEP
Prog. Theor. Exp. Phys. 2022 053B02(16 pages)
DOI: 10.1093/ptep/ptac059

μTRISTAN

al. '22

μ^+e^- collisions would make μTRISTAN
an ideal environment to study cLFV!

For possible applications see
Fridell et al. ‘23, Lichtenstein et al. ’23

- Th … PARC
  [A
- Th … with :

→ “Higgs factory” with $\sqrt{s} \simeq 346$ GeV
→ Expected integrated luminosity $\mathcal{L} = 1$ ab^{-1}

OR

→ “Discovery machine” with $\sqrt{s} = 2$ TeV
→ Expected integrated luminosity $\mathcal{L} = 100$ fb^{-1}

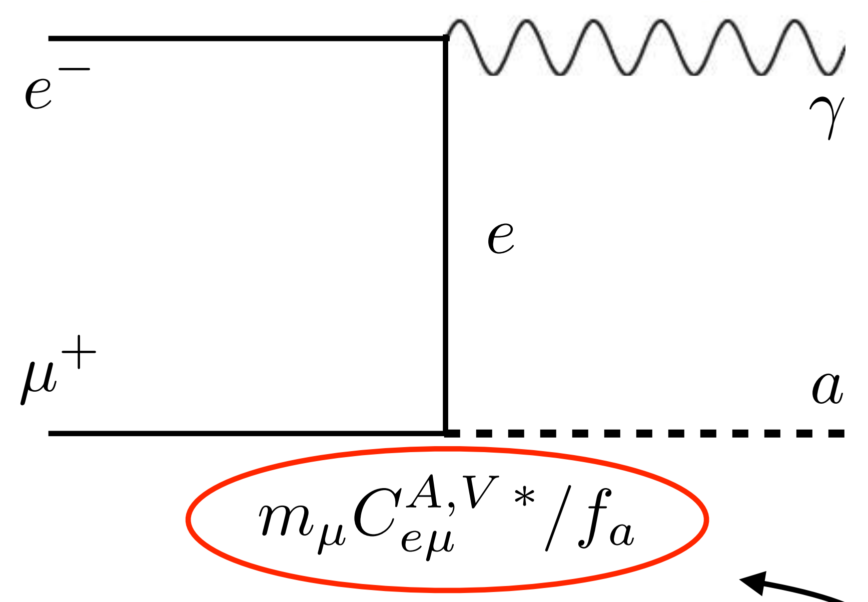
slide borrowed from L. Mukherjee

Most promising production mode
(*see backup for other processes*):

$$\sigma(e^-\mu^+ \to a\gamma) \simeq \alpha \frac{m_\mu^2}{f_a^2} \frac{|C_{e\mu}^A|^2 + |C_{e\mu}^V|^2}{4s} |\eta|_{\max}$$

$$= \; 0.03 \text{ fb} \left(\frac{200\text{ GeV}}{F_{e\mu}}\right)^2 \left(\frac{346\text{ GeV}}{\sqrt{s}}\right)^2 \left(\frac{|\eta|_{\max}}{2.5}\right)$$

LC Li Mukherjee Yang '24



Heavier ALPs can decay promptly through the same LFV interactions

Charge combination $a \to \mu^- e^+$ virtually background-free:

Signal: $e^-\mu^+ \to \gamma a \to \gamma \mu^- e^+$

SM bg: $e^-\mu^+ \to \gamma \nu_e \bar{\nu}_\mu W^-(\to \mu^- \bar{\nu}_\mu) W^+(\to e^+ \nu_e)$ $[\sigma_B \simeq 2 \times 10^{-5}\text{ fb}]$

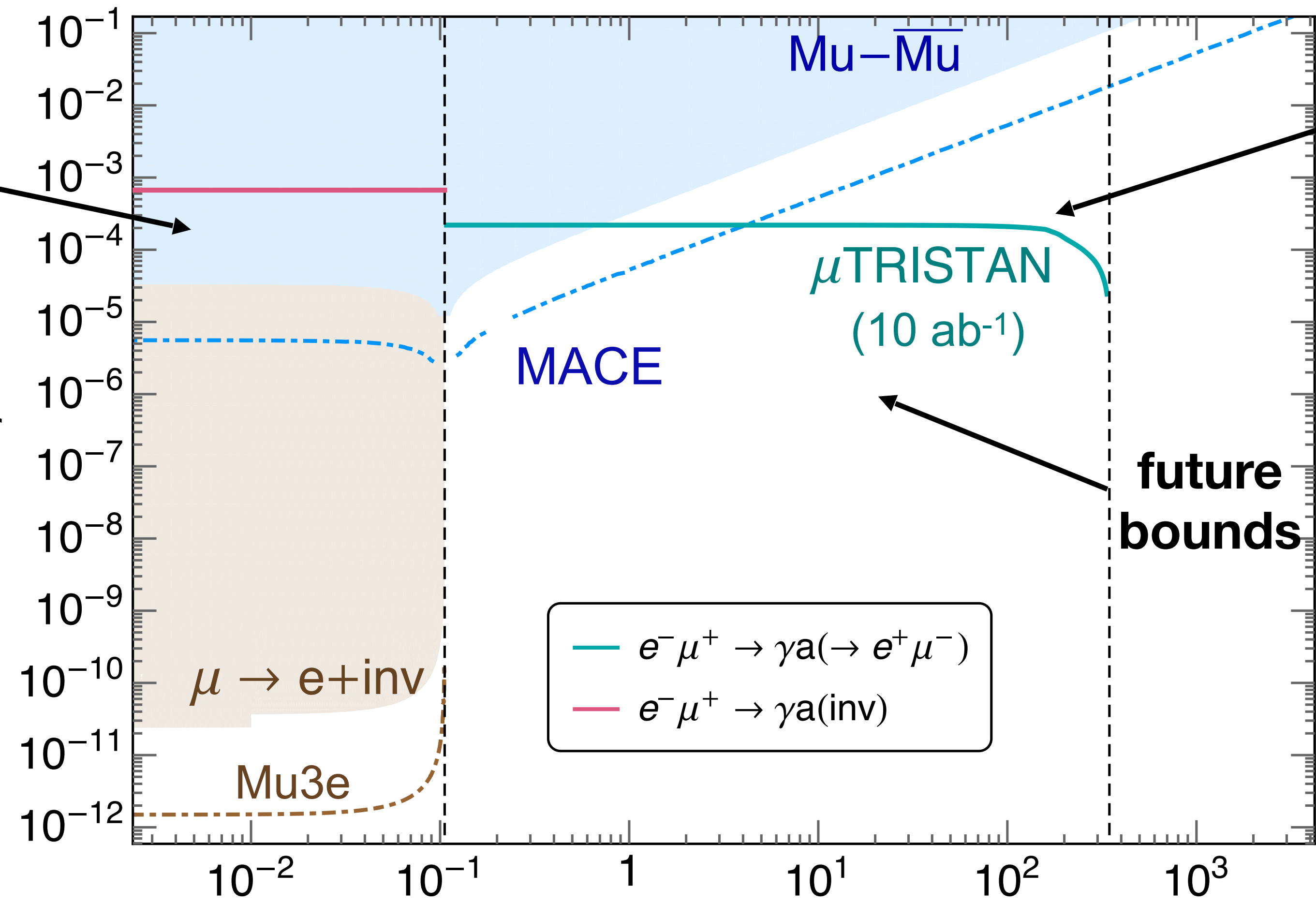
However, asymmetric beams reduce signal efficiency:

About 70% (50%) of ALP decay products fly outside the geometric acceptance for a detector with $|\eta|<2.5$ (3.5)

Future sensitivity to ALP μ-e interactions

Only LFV couplings $C_{e\mu}^{V,A}$

already excluded



$e^-\mu^+ \to \gamma a \to \gamma\mu^- e^+$

future bounds

ALP coupling

$$g_{e\mu}^{A,V} \simeq \frac{m_\mu C_{e\mu}^{A,V}}{2 f_a}$$

ALP mass →

LC Li Mukherjee Yang '24

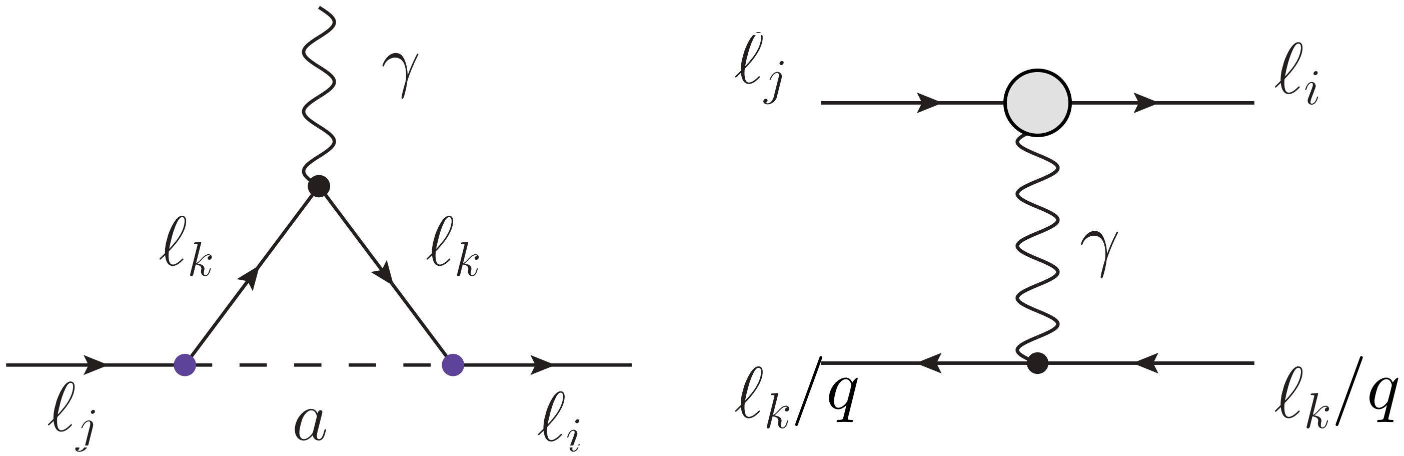
Interesting **interplay** between MACE and μTRISTAN

What if there are also substantial *flavour-conserving* (LFC) couplings?

One can also search for $a \to \mu^+\mu^-$ *but* low-energy LFV becomes stronger

ALP-induced muon LFV decays

Other interactions (LFC ones, in particular) lead to muon LFV decays:



see e.g. Cornella Paradisi Sumensari '19

Stringent limits from:

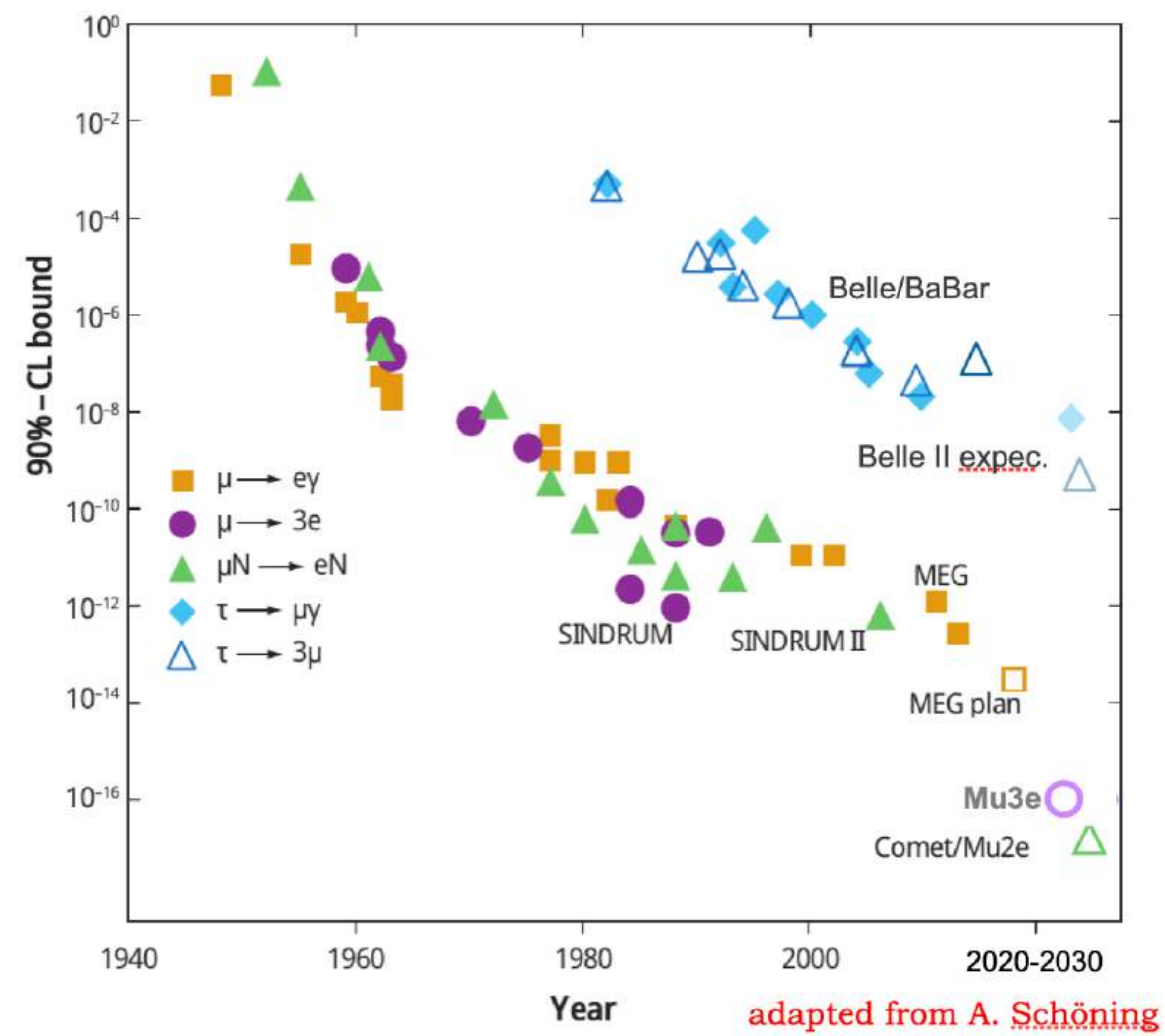
$$\mu \to e\gamma$$

$$\mu \to eee$$

$$\mu\,\mathrm{N} \to e\,\mathrm{N}$$

For a pedagogical introduction (exp + th)

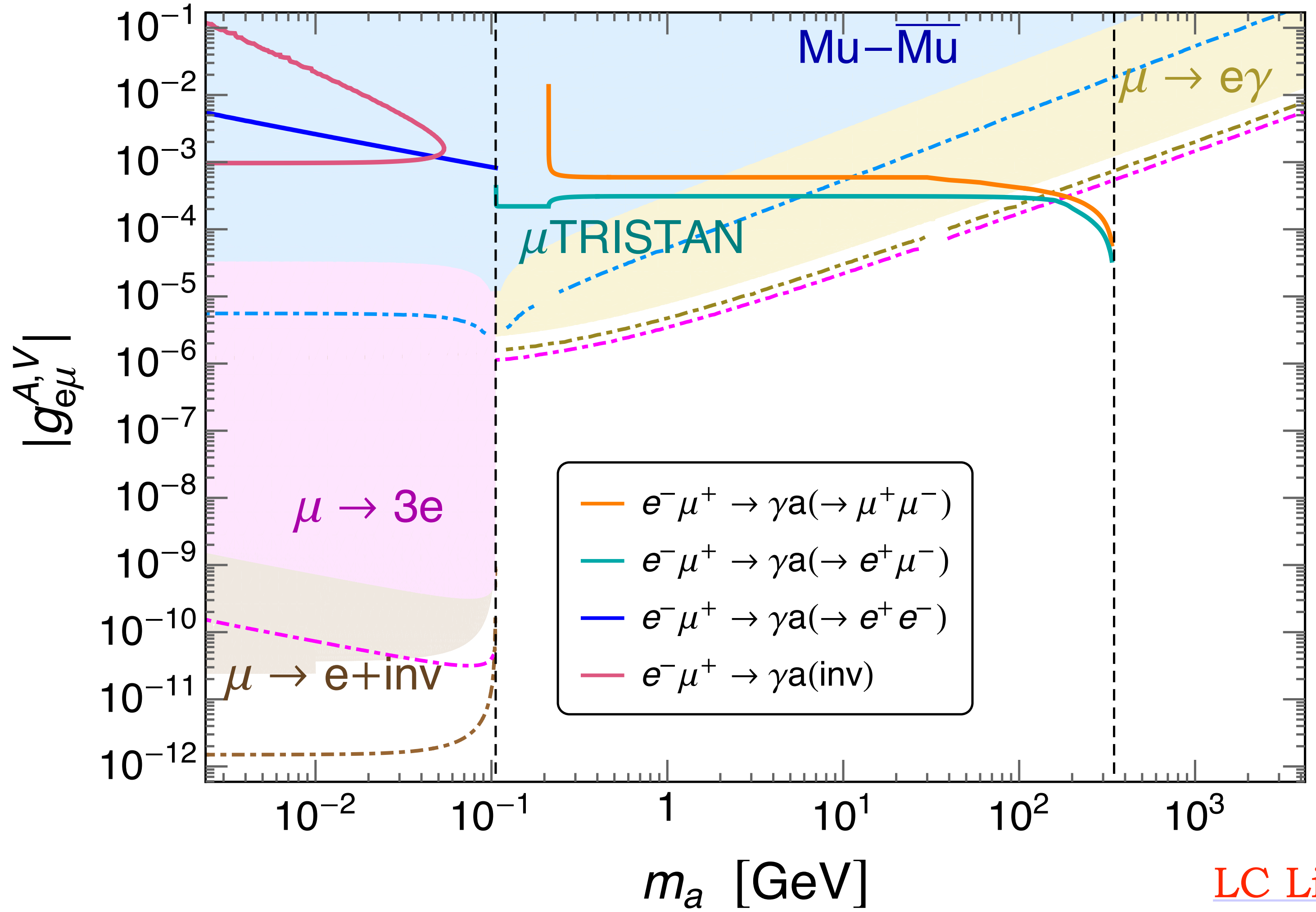
cf. LC and Signorelli '17



adapted from A. Schöning

Future sensitivity to ALP μ-e interactions

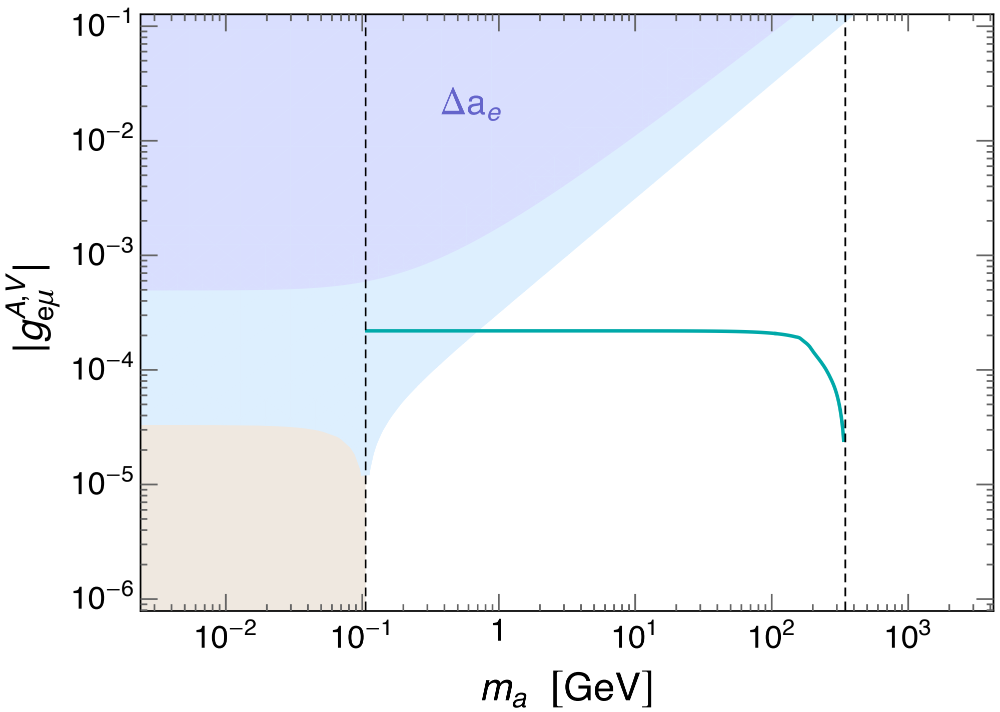
LFV+LFC: $C^{V,A}_{e\mu} = C^{A}_{ee} = C^{A}_{\mu\mu}$



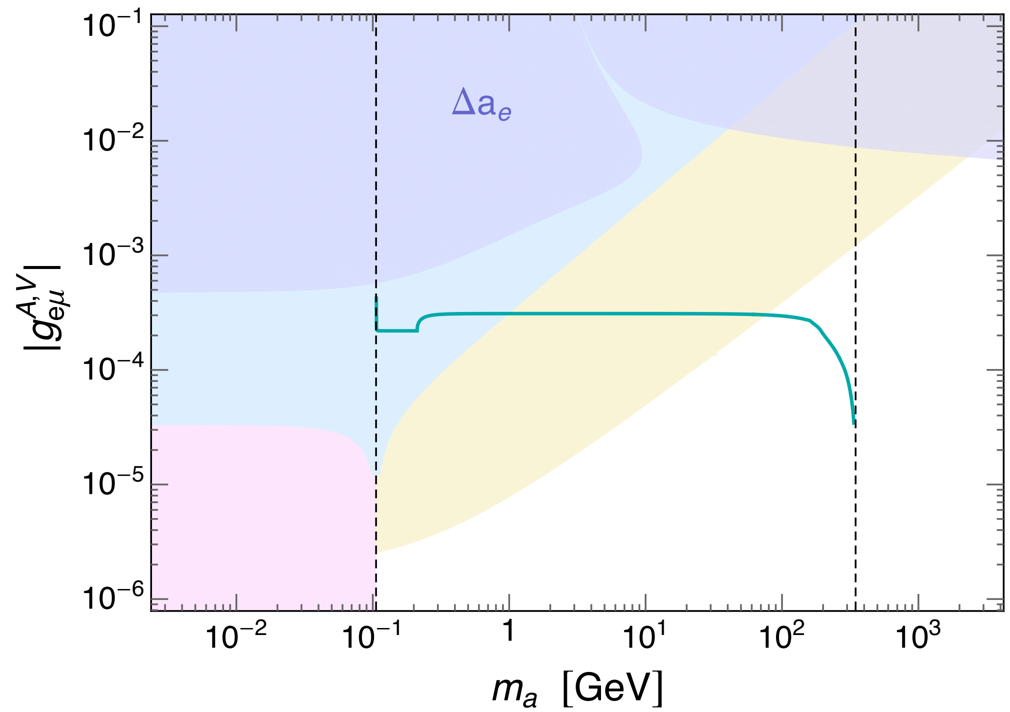
LC Li Mukherjee Yang '24

μTRISTAN sensitivity could go beyond low-energy LFV constraints, only for very heavy ALPs, $m_a \gtrsim O(100)$ GeV

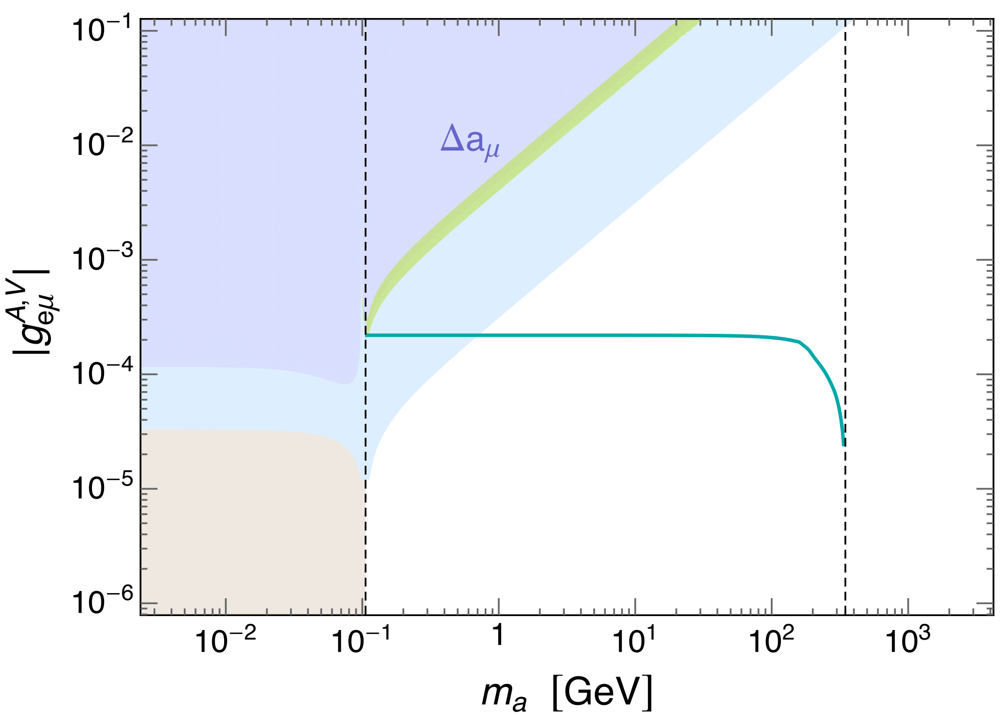
Muon and electron g-2 constraints



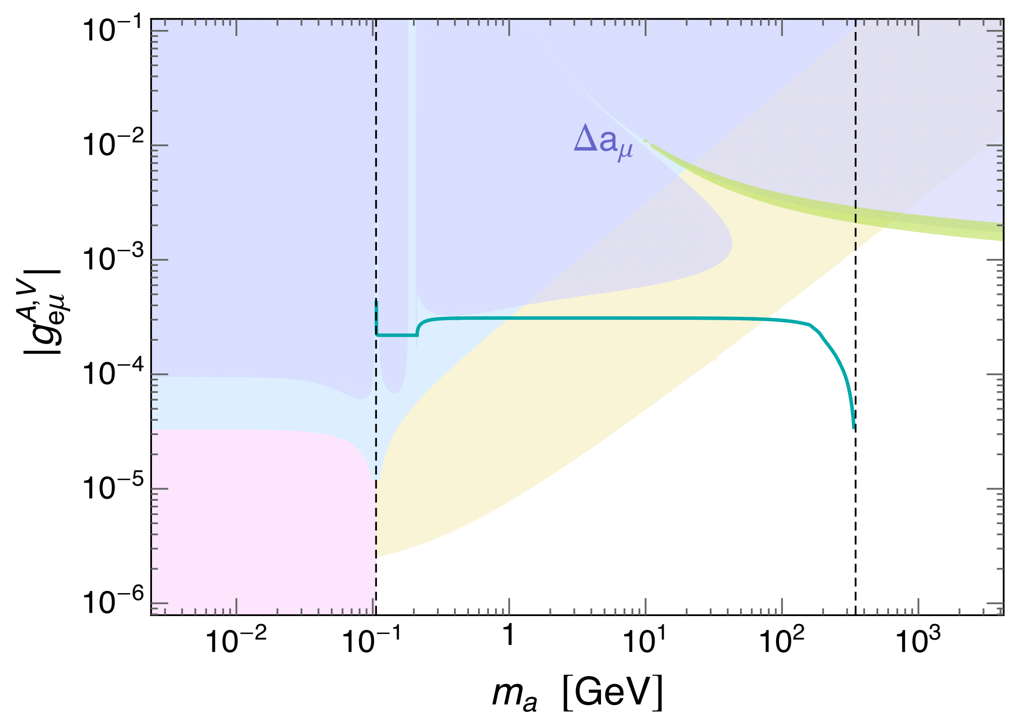
(a) LFV (e-μ) couplings only



(b) LFV (e-μ) and LFC couplings



(c) LFV (e-μ) couplings only



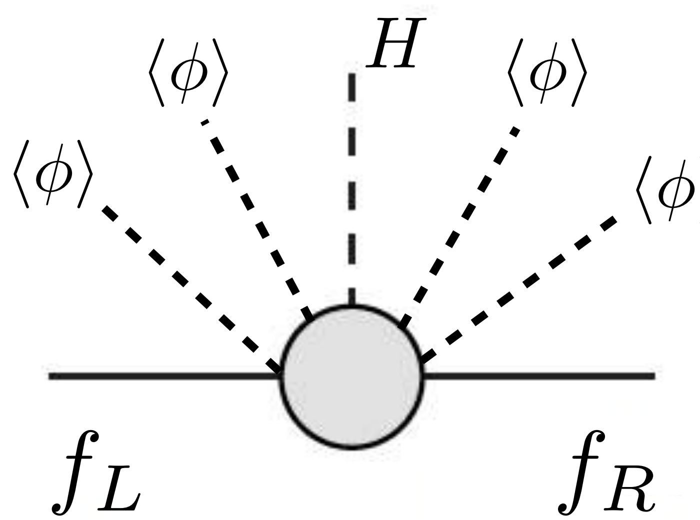
(d) LFV (e-μ) and LFC couplings

- 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
...

$$-\mathcal{L} = a^u_{ij} \left(\frac{\phi}{\Lambda}\right)^{n^u_{ij}} \overline{Q}_i u_j \tilde{H} + a^d_{ij} \left(\frac{\phi}{\Lambda}\right)^{n^d_{ij}} \overline{Q}_i d_j H$$

flavour-anarchical
O(1) coefficients



$\langle\phi\rangle < \Lambda$ ⇨ $\epsilon \equiv \langle\phi\rangle/\Lambda$ small expansion parameter (Λ=UV scale)

n^f_{ij} dictated by the symmetry

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

The simplest option: Froggatt-Nielsen U(1)

Quark sector

FN charges

	ϕ	Q_i	u_i	d_i	H
U(1)	1	$\mathcal{Q}_{Q_i}$	$\mathcal{Q}_{u_i}$	$\mathcal{Q}_{d_i}$	0

$\Rightarrow$

$$Y^u_{ij} = a^u_{ij}\,\epsilon^{\mathcal{Q}_{Q_i}-\mathcal{Q}_{u_j}}$$

$$Y^d_{ij} = a^d_{ij}\,\epsilon^{\mathcal{Q}_{Q_i}-\mathcal{Q}_{d_j}}$$

Rotation matrices $Y^f = V^{f\dagger}\hat{Y}^f W^f$ $\Rightarrow$ $V^{u,d}_{ij} \sim \epsilon^{|\mathcal{Q}_{Q_i}-\mathcal{Q}_{Q_j}|}$ $W^{u,d}_{ij} \sim \epsilon^{|\mathcal{Q}_{u_i,d_i}-\mathcal{Q}_{u_j,d_j}|}$

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:

$$(\mathcal{Q}_{Q_1},\,\mathcal{Q}_{Q_2},\,\mathcal{Q}_{Q_3}) = (3,\,2,\,0),\quad (\mathcal{Q}_{u_1},\,\mathcal{Q}_{u_2},\,\mathcal{Q}_{u_3}) = (-4,\,-2,\,0),\quad (\mathcal{Q}_{d_1},\,\mathcal{Q}_{d_2},\,\mathcal{Q}_{d_3}) = (-4,\,-2,\,-2)$$

$$Y^u \sim \begin{pmatrix} \epsilon^7 & \epsilon^5 & \epsilon^3 \\ \epsilon^6 & \epsilon^4 & \epsilon^2 \\ \epsilon^4 & \epsilon^2 & 1 \end{pmatrix}, \quad Y^d \sim \begin{pmatrix} \epsilon^7 & \epsilon^5 & \epsilon^5 \\ \epsilon^6 & \epsilon^4 & \epsilon^4 \\ \epsilon^4 & \epsilon^2 & \epsilon^2 \end{pmatrix} \quad V_{\rm CKM} \sim \begin{pmatrix} 1 & \epsilon & \epsilon^3 \\ \epsilon & 1 & \epsilon^2 \\ \epsilon^3 & \epsilon^2 & 1 \end{pmatrix}$$

$$\epsilon = \langle\phi\rangle/\Lambda \approx 0.2$$

Lepton sector

$$-\mathcal{L} \supset \left[a^{\ell}_{ij} \left(\frac{\langle\phi\rangle}{\Lambda_\ell}\right)^{\mathcal{Q}_{L_i}-\mathcal{Q}_{e_j}} \overline{L}_i e_j H + h.c.\right] + \kappa^{\nu}_{ij} \left(\frac{\langle\phi^*\rangle}{\Lambda_\ell}\right)^{\mathcal{Q}_{L_i}+\mathcal{Q}_{L_j}} \frac{(\overline{L^c_i}\,\tilde{H})(\tilde{H}^T L_j)}{\Lambda_N}$$

$$\Rightarrow\ Y^\ell = V^\ell \hat{Y}^\ell W^{\ell\dagger}, \qquad m^\nu = V^\nu \hat{m}^\nu V^{\nu T} \qquad V^{\ell,\nu}_{ij} \sim \epsilon_\ell^{\left|\mathcal{Q}_{L_i}-\mathcal{Q}_{L_j}\right|}, \qquad W^\ell_{ij} \sim \epsilon_\ell^{\left|\mathcal{Q}_{e_i}-\mathcal{Q}_{e_j}\right|}$$

LH charges can chosen to give a (quasi-)anarchical $U_{\rm PMNS} = V^\nu V^{\ell\,\dagger}$
RH charges then responsible for charged leptons hierarchy

Examples:

Altarelli Feruglio Masina Merlo '12

- Anarchy $(\mathcal{Q}_{L_1}, \mathcal{Q}_{L_2}, \mathcal{Q}_{L_3}) = (\mathcal{Q}_L, \mathcal{Q}_L, \mathcal{Q}_L)$
- Mu-tau anarchy $(\mathcal{Q}_{L_1}, \mathcal{Q}_{L_2}, \mathcal{Q}_{L_3}) = (\mathcal{Q}_L+1, \mathcal{Q}_L, \mathcal{Q}_L)$
- Hierarchy $(\mathcal{Q}_{L_1}, \mathcal{Q}_{L_2}, \mathcal{Q}_{L_3}) = (\mathcal{Q}_L+2, \mathcal{Q}_L+1, \mathcal{Q}_L)$

Charged lepton hierarchy, e.g. : $(\mathcal{Q}_{e_1}, \mathcal{Q}_{e_2}, \mathcal{Q}_{e_3}) = (\mathcal{Q}_L-4, \mathcal{Q}_L-2, \mathcal{Q}_L-1)$
(with $\epsilon_\ell \approx \epsilon^2 \approx 0.04$)

Local Froggatt-Nielsen U(1)

Flavour non-universal **local** U(1) symmetry generating the hierarchies of fermion masses and mixing through the Froggatt-Nielsen mechanism

(anomalies cancelled by suitable UV completions Smolkovič Tammaro Zupan '19 Bonnefoy Dudas Pokorski '19)

Below the cutoff Λ, only **two** new particles:

$$\phi = \frac{v_\phi + \varphi}{\sqrt{2}} e^{i a / v_\phi}$$

longitudinal component of

Physical flavon

$$m_\varphi^2 = \frac{1}{2}\lambda_\phi v_\phi^2$$

$$\mathcal{L} = n_{ij}^f \frac{m_{ij}^f}{v_\phi} \overline{f}_i P_R f_j \, \varphi$$

U(1) gauge boson, *Z'*

$$m_{Z'} = \sqrt{2}\, g_F \langle\phi\rangle = g_F\, v_\phi$$

$$\mathcal{L} \supset g_F \, \overline{f} \gamma^\mu (\mathcal{Q}_{f_L} P_L + \mathcal{Q}_{f_R} P_R) f \; Z'_\mu$$

→ both fields decay into SM fermions and are produced in the early universe by thermal interactions (O(1) couplings with the fields at Λ)

→ we have to require their lifetime < 0.1 s in order not to affect **BBN**