Searching for Heavy QCD Axions via Dimuon Final States

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w/ Raymond Co and Zhen Liu, 2210.02462
w/ ArgoNeuT Collaboration, 2207.08448

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Strong *CP* Problem

$$\mathscr{L}_{\text{SM}} \supset \frac{\alpha_3}{8\pi}\theta G\tilde{G} + Y_u \bar{Q}_L \tilde{H} u_R + Y_d \bar{Q}_L H d_R$$

- Observed $|\bar{\theta}| = |\theta + \arg\det(Y_u Y_d)| < 10^{-10}$

Neutron EDM,
Abel et. al. 2001.11966

- But why so small given $\delta_{\text{CKM}} \sim \mathcal{O}(1)$?

strong *CP* problem

- Solutions: ~~massless up quark~~, parity, *CP*, axions

lattice results

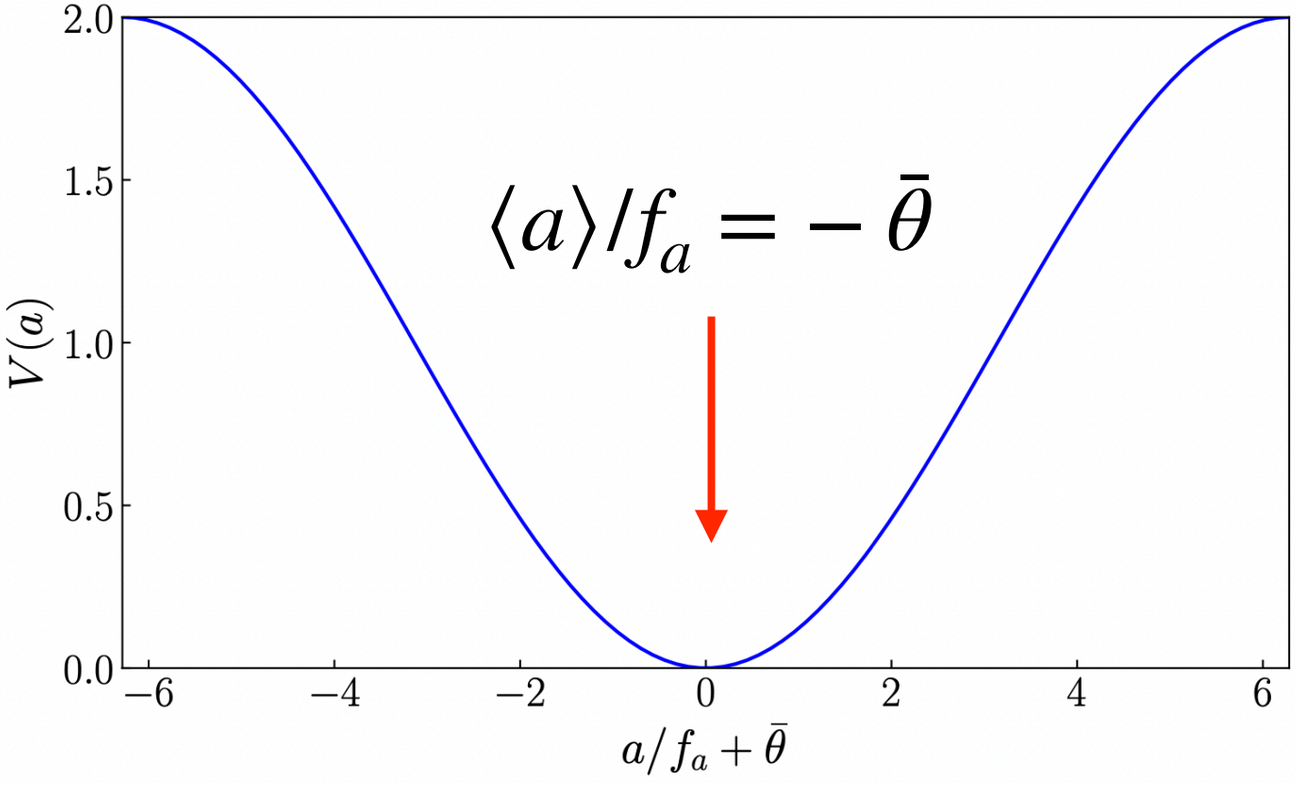
Axion Solution

- Axion solution:

Peccei, Quinn '77
Weinberg, Wilczek '78

$\bar{\theta}$ is a dynamical quantity

$$\mathscr{L}_{\text{SM+Axion}} \supset \frac{\alpha_3}{8\pi}\left(\bar{\theta} + \frac{a}{f_a}\right) G\tilde{G} \Rightarrow V(a) \approx -m_\pi^2 f_\pi^2 \cos\left(\frac{a}{2f_a} + \frac{\bar{\theta}}{2}\right)$$



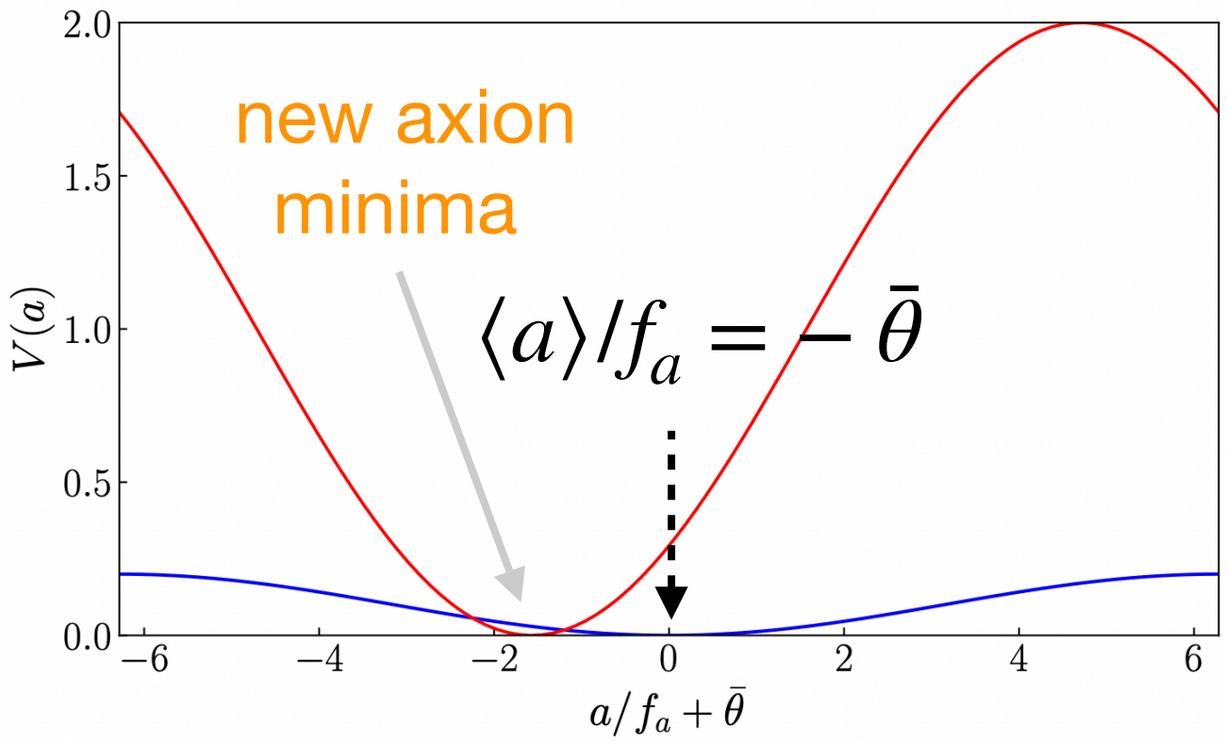
$$\bar{\theta}_{\text{eff}} = \bar{\theta} + \langle a \rangle / f_a = 0!$$

elegant solution from IR EFT point of view

Axion Quality Problem

- But not so elegant from UV! Imagine a arising as a Goldstone from Peccei-Quinn scalar $\Phi \sim f_a e^{ia/f_a}$

$$\frac{\Phi^N}{M_{pl}^{N-4}} \Rightarrow V(a) \approx -m_\pi^2 f_\pi^2 \cos\left(\frac{a}{2f_a} + \frac{\bar{\theta}}{2}\right) + \frac{f_a^N}{M_{pl}^{N-4}} \cos\left(\frac{Na}{f_a} + \delta\right)$$



$\bar{\theta}_{\rm eff} = \bar{\theta} + \langle a \rangle / f_a \sim \mathcal{O}(1)$!
strong *CP* problem reappears!

Kamionkowski et al.,
Barr et al., Holman et al.,
Ghigna et al. ’92

Axion Quality Problem

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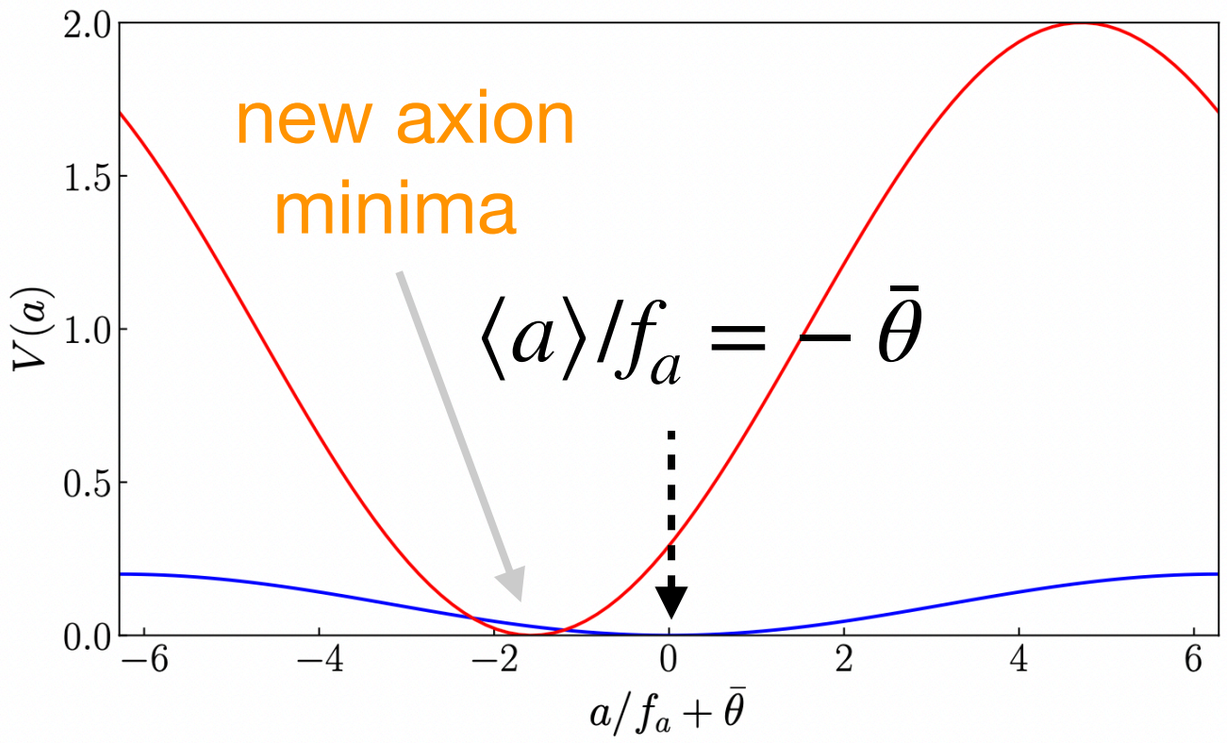
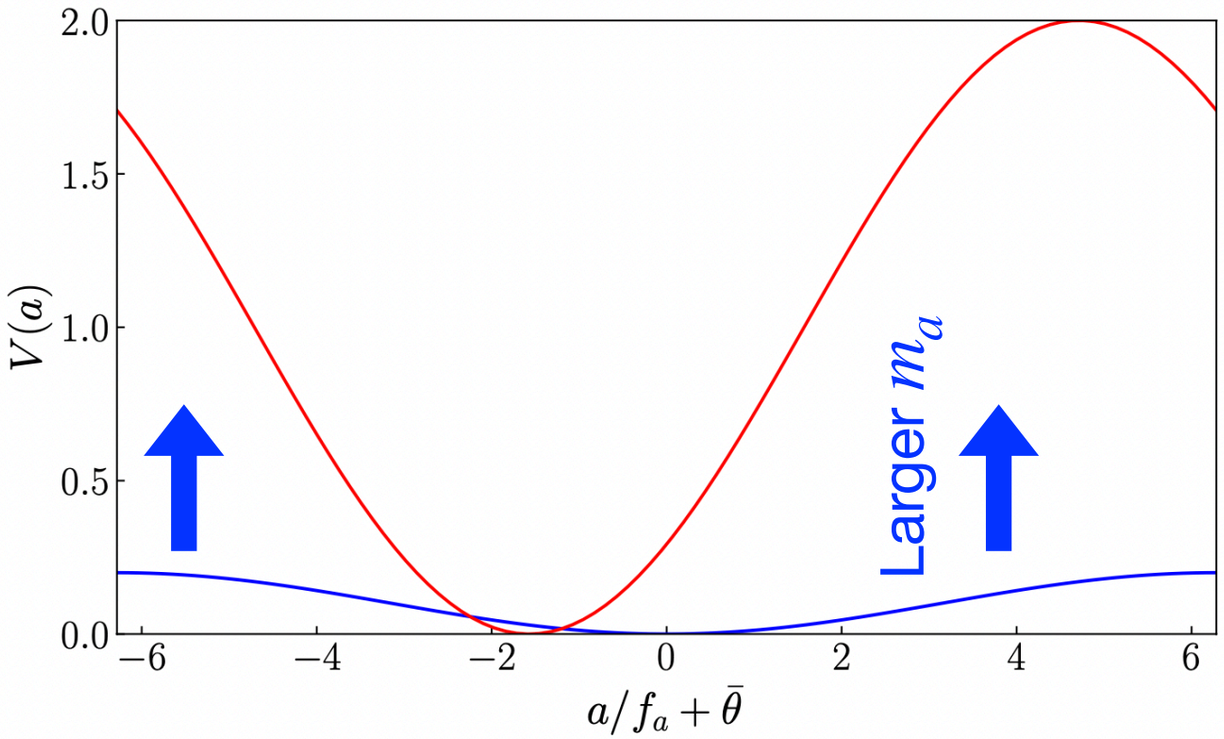


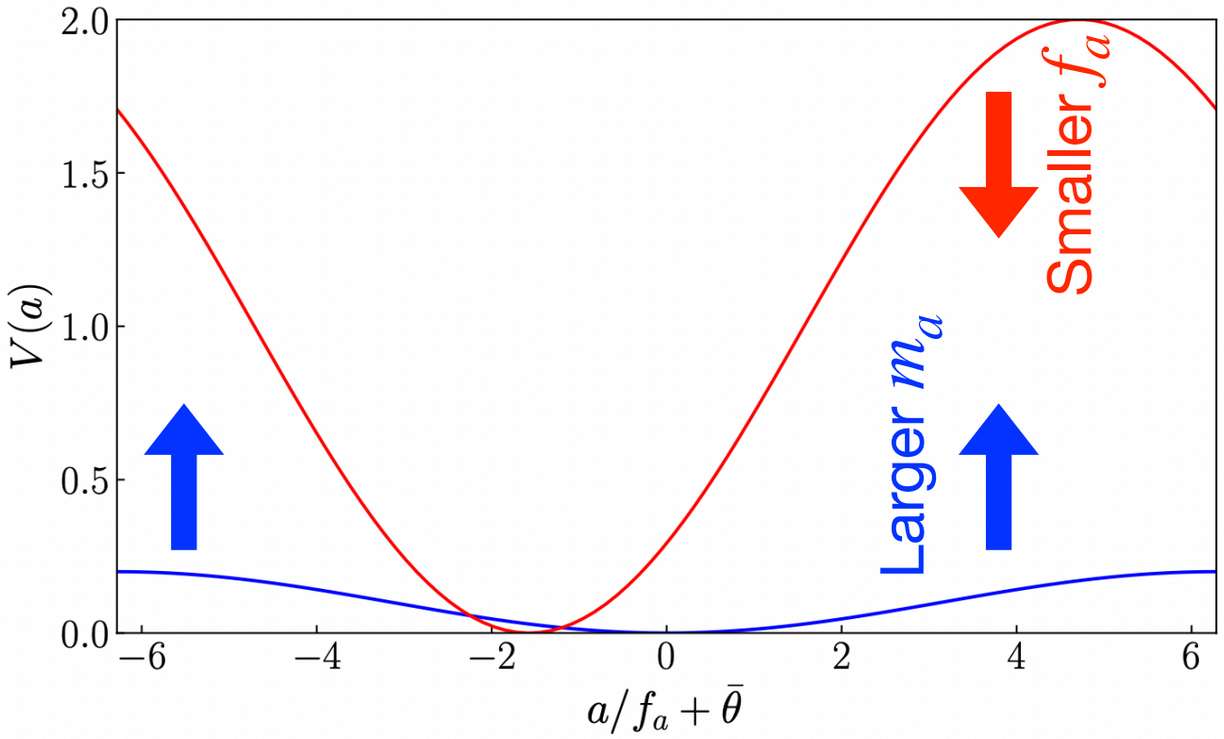
In summary, these dangerous contribution can spoil the solution to the strong CP problem

Sketching Solutions



- Since $V_{\mathrm{QCD}}(a) \sim m_a^2 a^2$, raising the axion mass strengthens the axion potential

Sketching Solutions



- Since $V_{\rm QCD}(a) \sim m_a^2 a^2$, raising the axion mass strengthens the axion potential

- The corrections are given by $f_a^N / M_{\rm pl}^{N-4}$

- If f_a is on the smaller side, of $\mathcal{O}$(TeV-PeV), that already suppresses these

- Larger m_a and smaller f_a : terrestrially observable!

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Heavy Axion Mass and Coupling

- Axion couples to another dark $SU(N)$ sector.
- $SU(N)$ confines at a scale higher than $\Lambda_{\rm QCD}$ it will raise the axion mass $m_a f_a \approx \Lambda_D^2 \gg \Lambda_{\rm QCD}^2$
- Axion coupling in the IR EFT

Several studies focused on photon and gluon coupling alone

$$\mathscr{L}_{\rm gauge} \supset c_3 \frac{\alpha_s}{8\pi f_a} a G\tilde{G} + c_2 \frac{\alpha_2}{8\pi f_a} a W\tilde{W} + c_1 \frac{\alpha_1}{8\pi f_a} a B\tilde{B}$$

$$\mathscr{L}_{\rm lepton} \supset \sum_{\ell=e,\mu,\tau} \frac{\partial_\mu a}{2f_a} c_\ell \bar{\ell}\gamma^\mu\gamma_5\ell$$

Co, **SK**, Liu 2210.02462

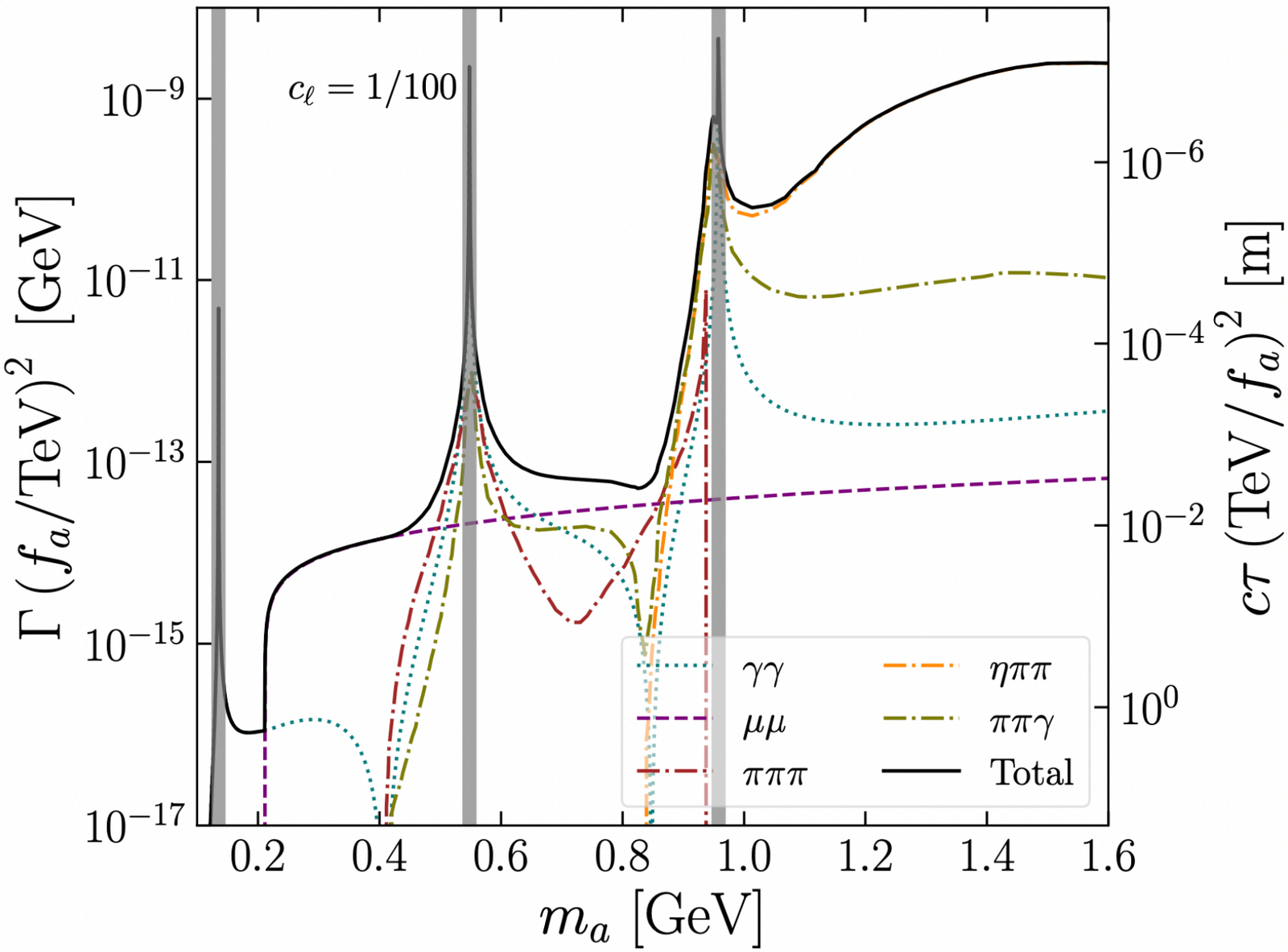
Axion Lifetime

- $aG\tilde{G}$ coupling introduces axion-pseudo scalar mixing

- Plays a role in production

- Macroscopic decay length for $0.2 \lesssim m_a \lesssim 1$ GeV

Hadronic rates from Aloni et al. 1811.03474



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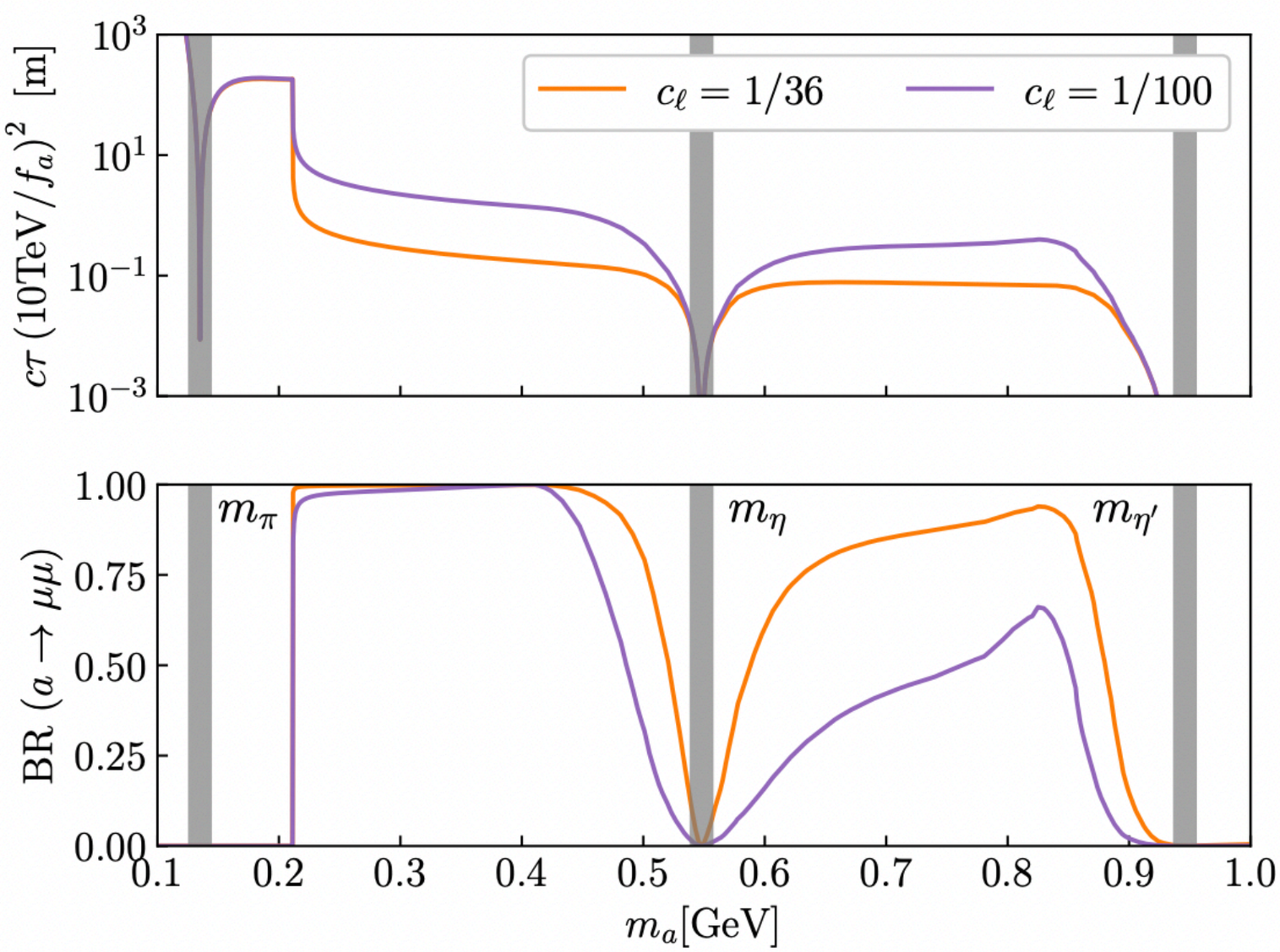
Dimuon Mode



- Dimuon could be an exciting discovery channel!

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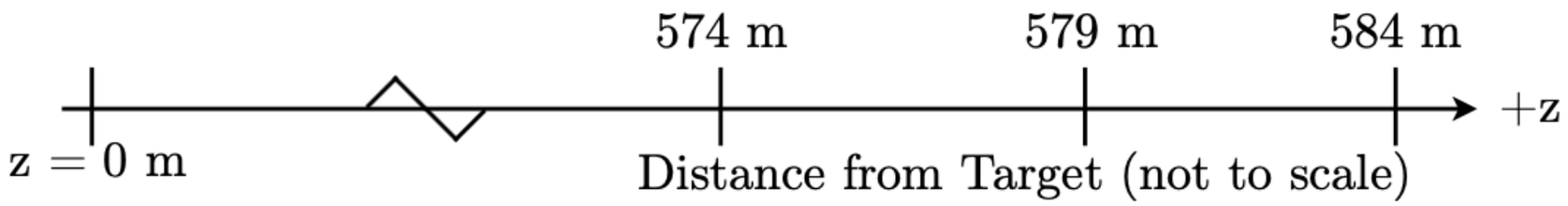
Beam Dump Schematic (DUNE)



Production with meson mixing (`Pythia` simulation)

$$\theta_{a\pi} = \frac{1}{6}\frac{f_\pi}{f_a}\frac{m_a^2}{m_a^2 - m_\pi^2}, \theta_{a\eta} = \frac{1}{\sqrt{6}}\frac{f_\pi}{f_a}\frac{m_a^2 - 4m_\pi^2/9}{m_a^2 - m_\eta^2}, \theta_{a\eta'} = \frac{1}{2\sqrt{3}}\frac{f_\pi}{f_a}\frac{m_a^2 - 16m_\pi^2/9}{m_a^2 - m_{\eta'}^2}.$$

Kelly, **SK**, Liu 2011.05995

Extending to Other Experiments

	E_p (GeV)	N_{POT}	d (m)	L (m)	$w \times h$ (m×m)
DUNE [79, 80]	120	1.47×10^{22}	574	$5 + 5$	7×3 $(r_{\mathrm{eff}} = 2.6\ \mathrm{m})$
SBND [81] BNB	8	6.6×10^{20}	110	5	4×4 $(r_{\mathrm{eff}} = 2.3\ \mathrm{m})$
SBND [81] NuMI	120	3×10^{21}	410		
MicroBooNE [81, 82] BNB	8	1.32×10^{21}	470	10.4	2.6×2.3 $(r_{\mathrm{eff}} = 1.4\ \mathrm{m})$
MicroBooNE [81, 82] NuMI	120	3×10^{21}	685		
ICARUS [81] BNB	8	6.6×10^{20}	600	19.9	$(3.9 \times 3.6) \times 2$ $(r_{\mathrm{eff}} = 2.1\ \mathrm{m})$
ICARUS [81] NuMI	120	2.5×10^{21}	790		
SHiP [83]	400	2×10^{20}	70	50	5×10 $(r_{\mathrm{eff}} = 4.0\ \mathrm{m})$
FASER 2 [84, 85]	14000	1.1×10^{16} (LHC Run 3) 2.2×10^{17} (HL-LHC)	480	5	$r = 1$ m

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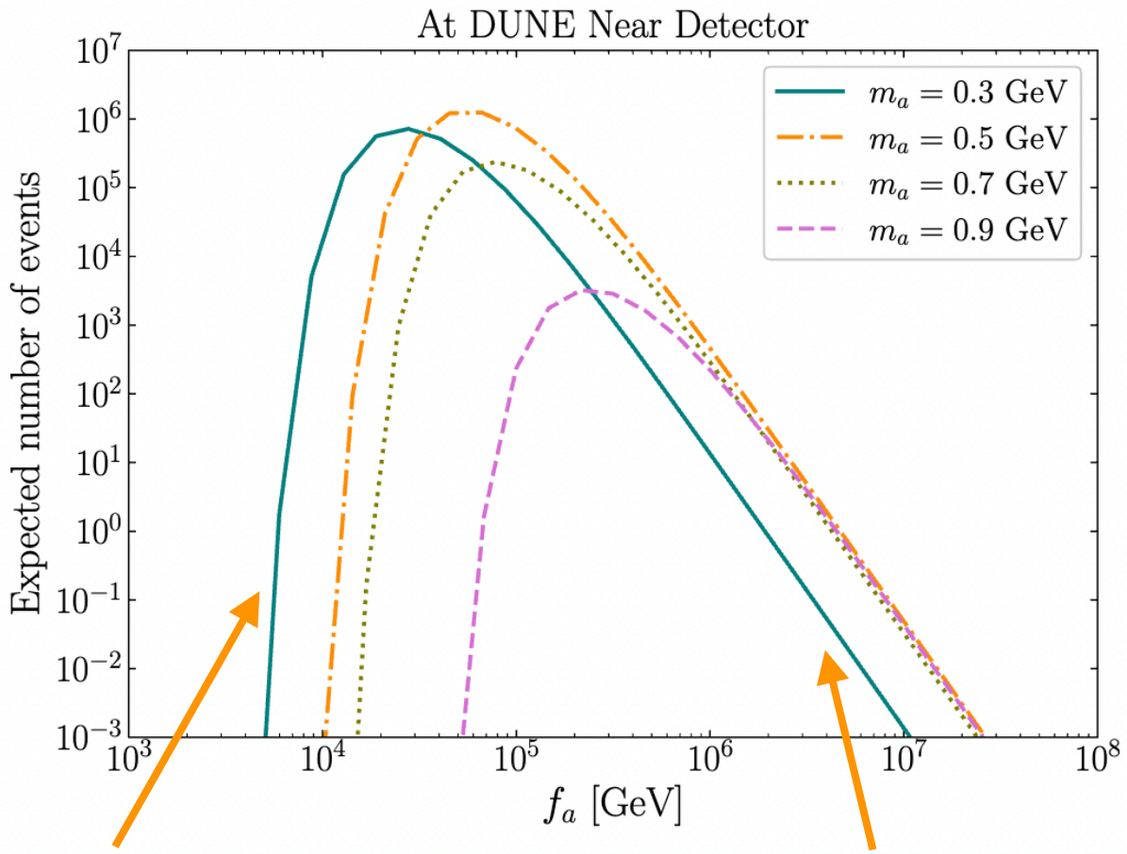
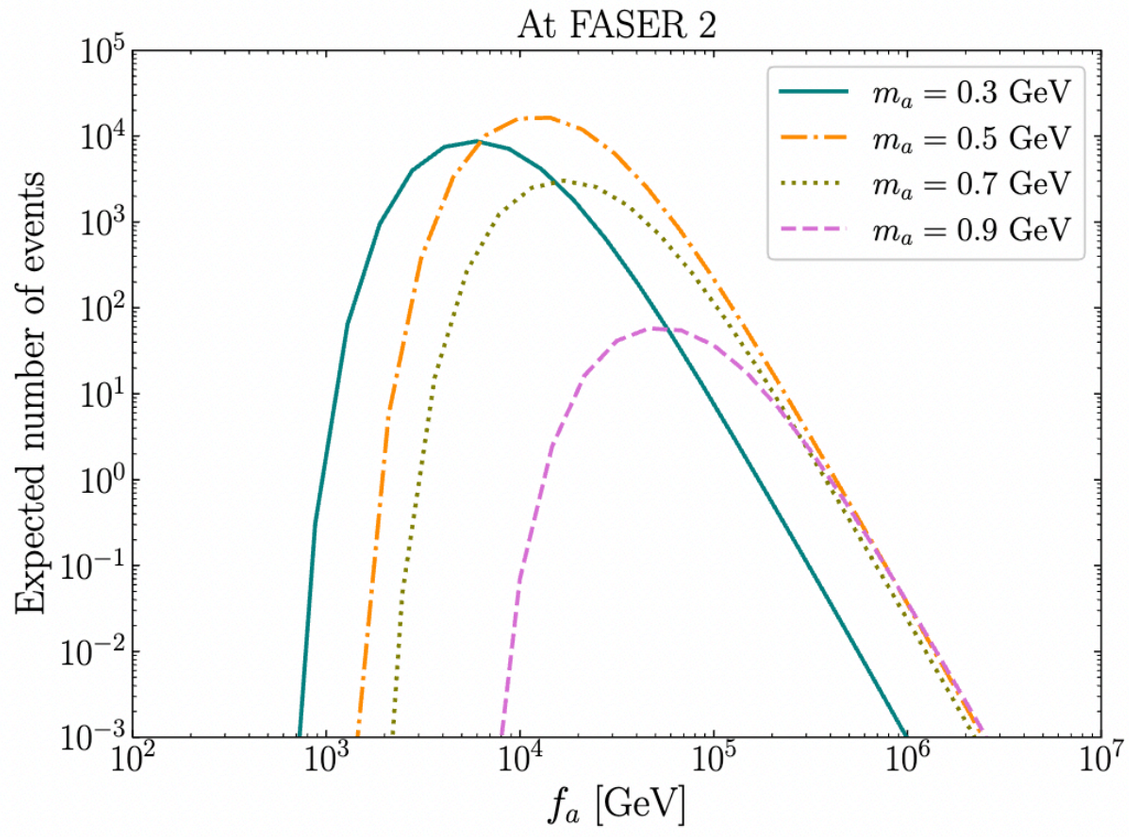
Number of Signal Events

- Survival probability $\left(e^{-\frac{d}{\gamma\beta c\tau}} - e^{-\frac{d+L}{\gamma\beta c\tau}}\right)$





exponential drop off, $\tau \ll d$

power law drop off, $\tau \gg d$

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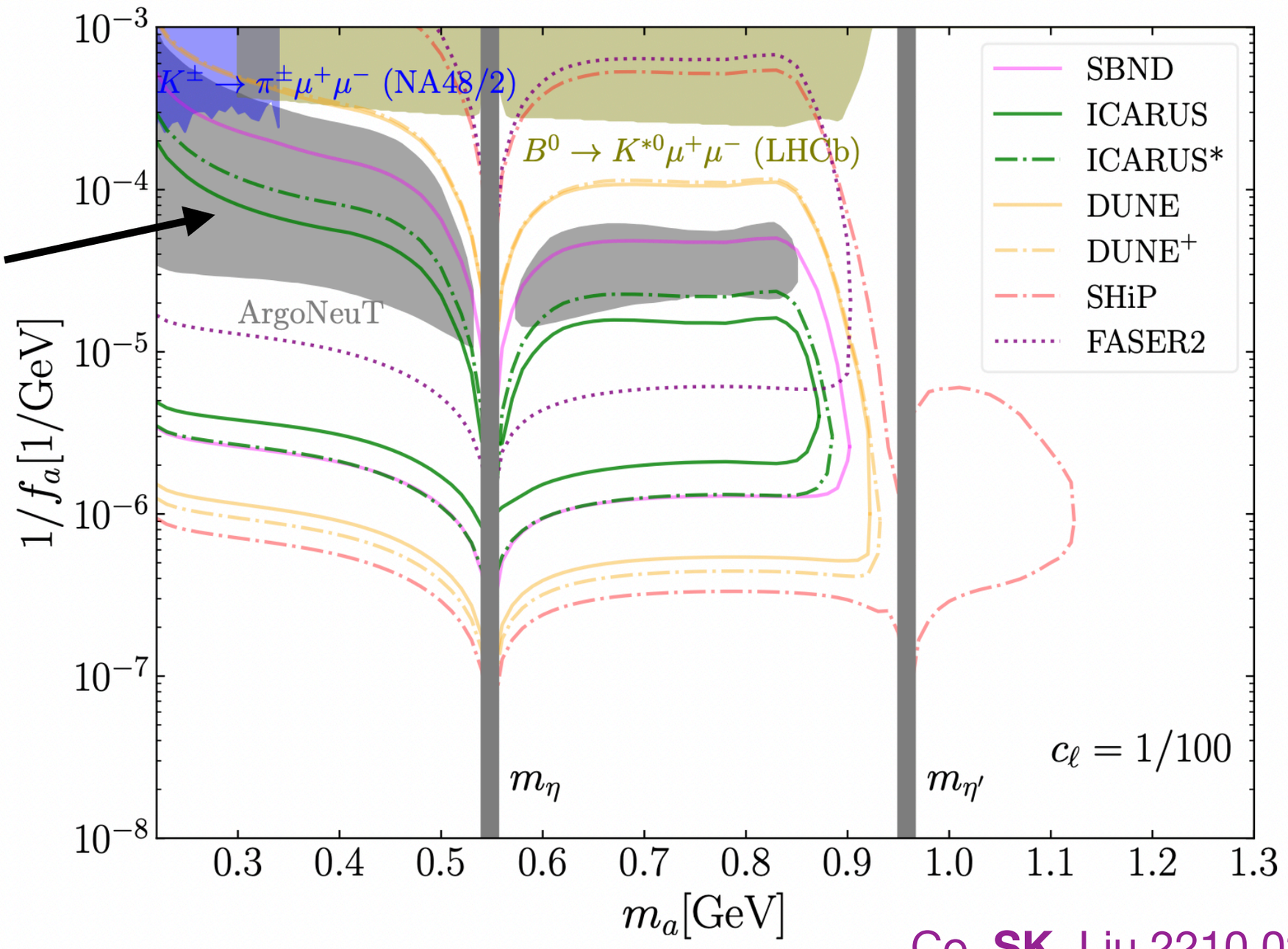
Results

Obtained in collaboration with ArgoNeuT
2207.08448



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Summary

- Heavy axions well motivated both from the perspective of quality problem and strong CP problem

- Obtained new constraints using existing ArgoNeuT data for $f_a \sim \mathrm{TeV} - 10^2\ \mathrm{TeV}$, GeV-scale axions

- Similar ideas can be applied in *e.g.*, SHiP, FASER, DUNE

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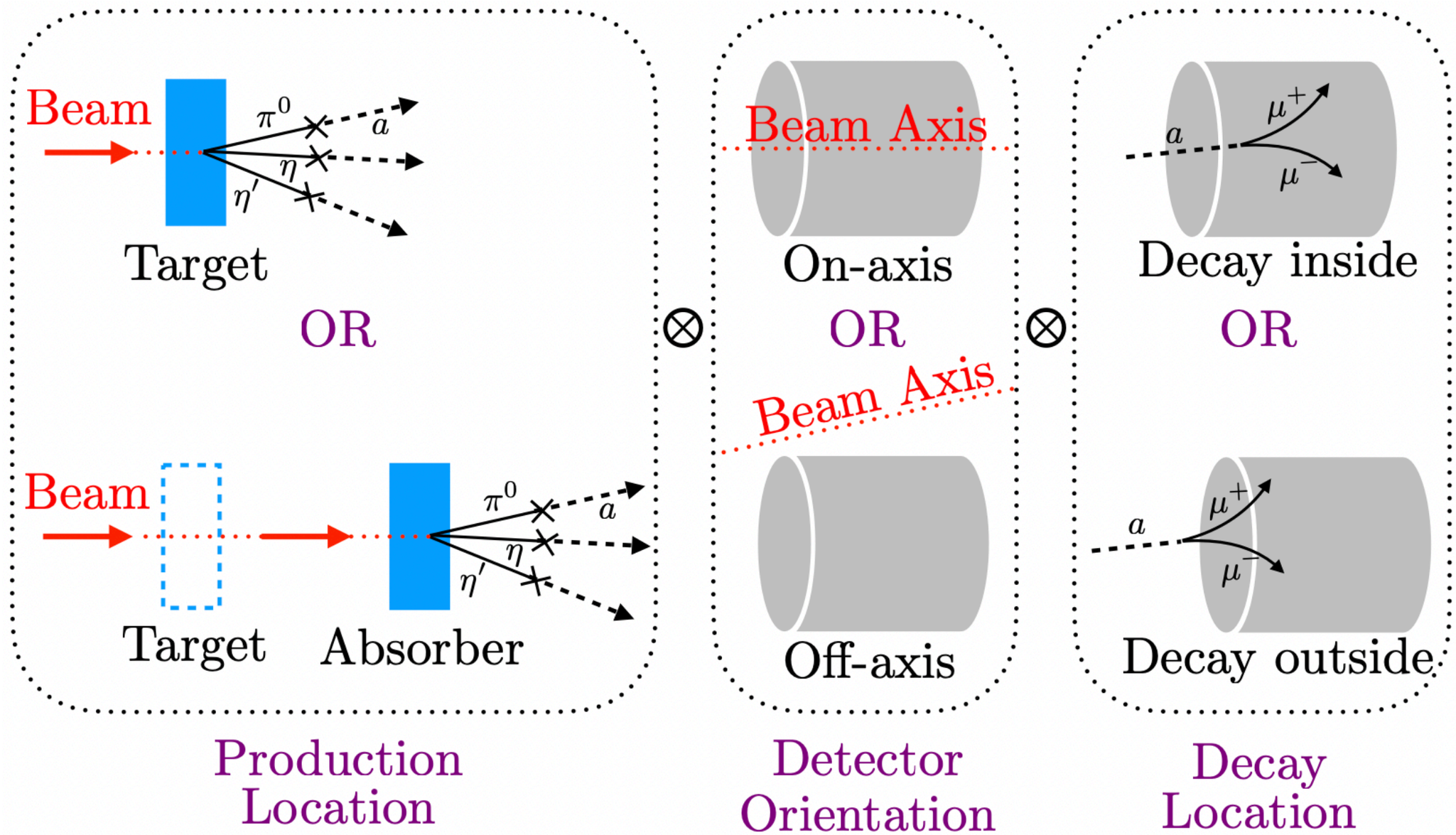
Thanks for your attention!

General Schematic



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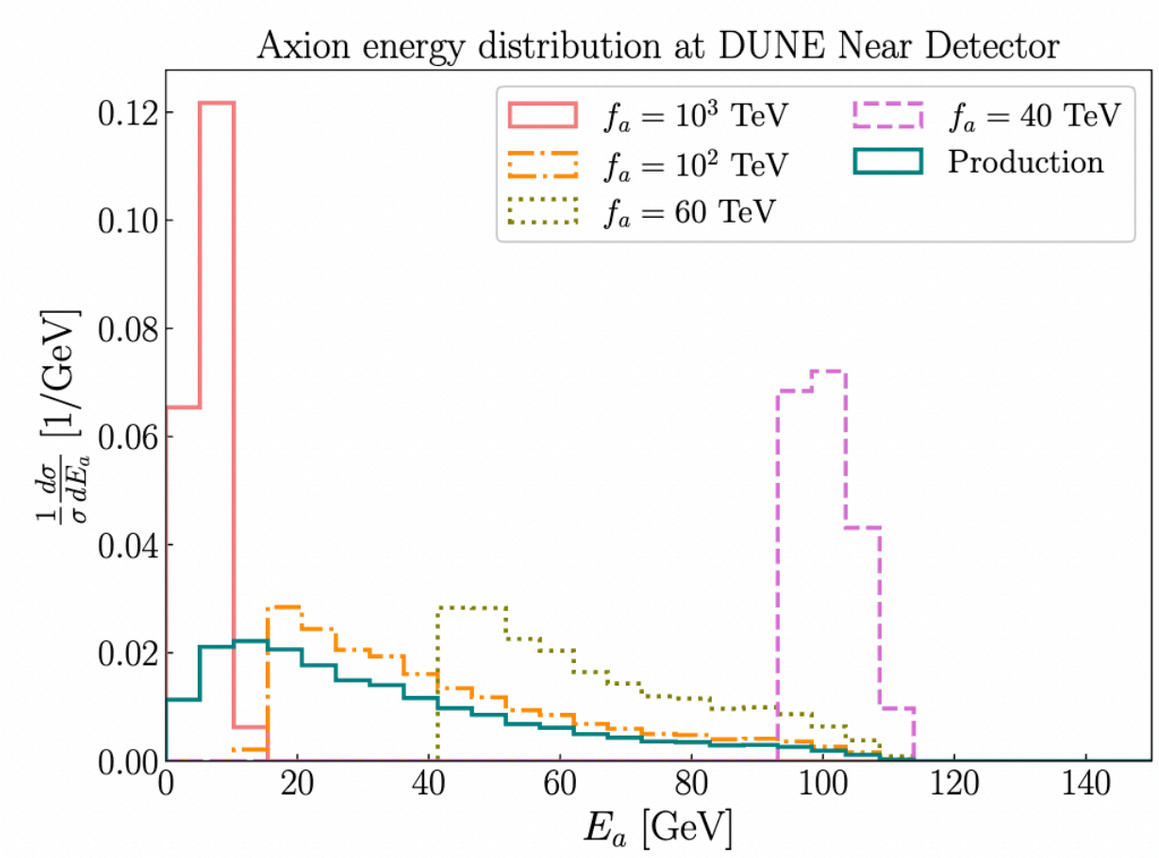
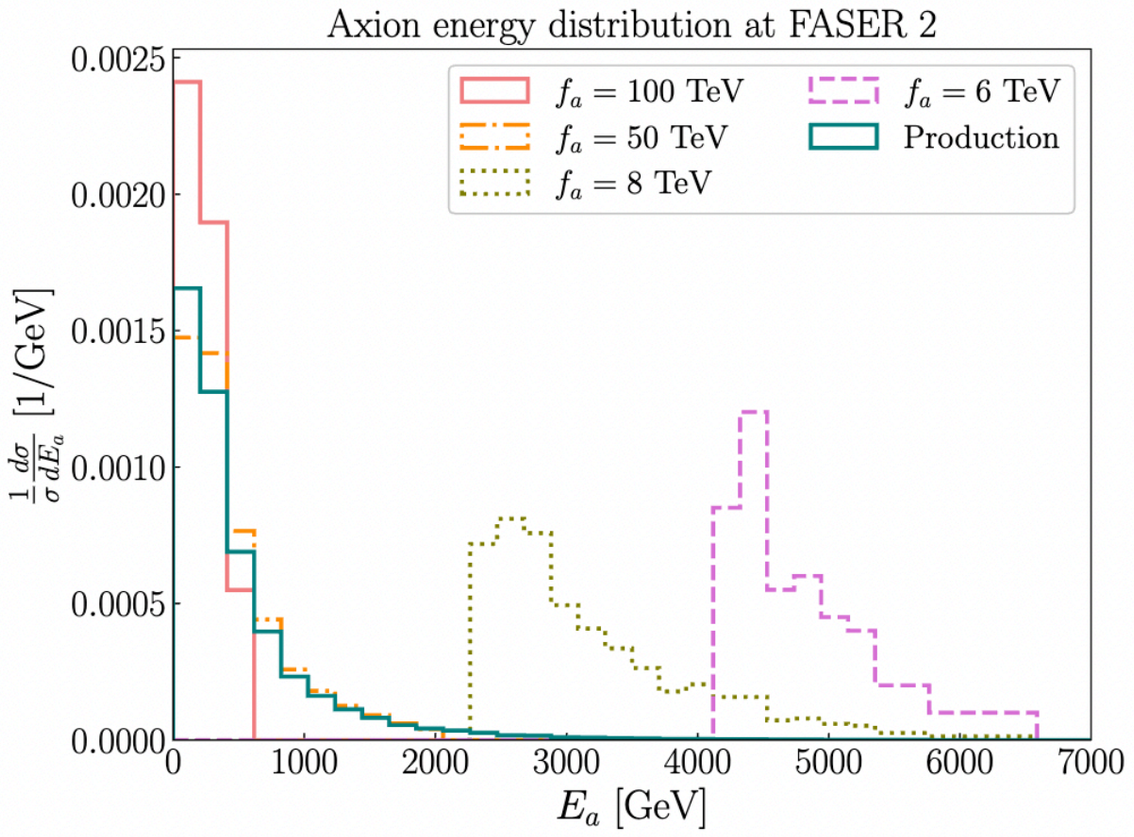
Energy Distribution of Axions





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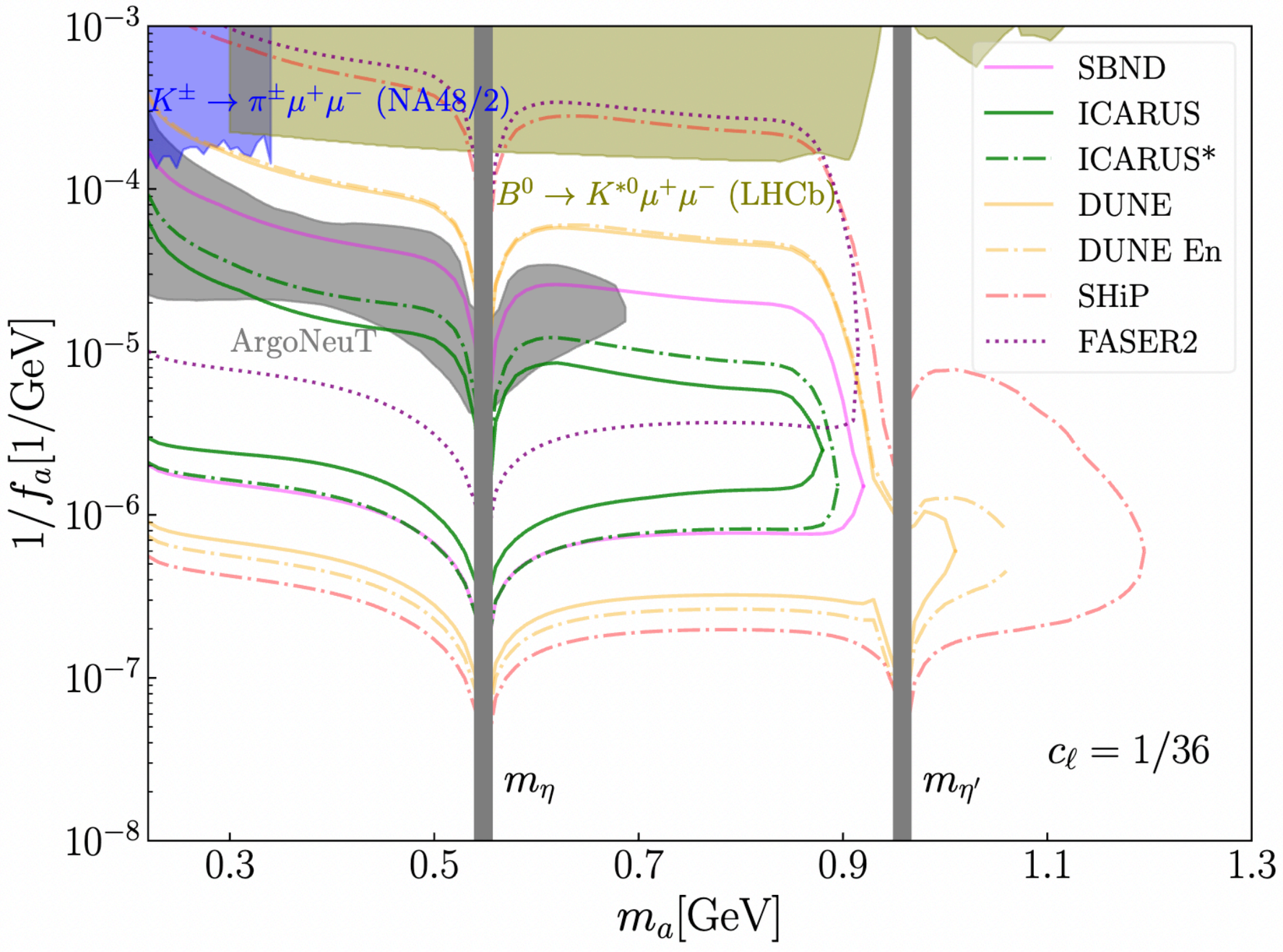
Varying Lepton Coupling



Example UV Completion

$$\mathscr{L} \supset y_{L_i} L_i l_i \Phi + y_{E_i} E_i e_i \Phi$$
$$+ y_Q Q Q^c \Phi + M_L L_i L_i^c + M_E E_i E_i^c + \cdots$$

$$\mathscr{L} \supset -\frac{1}{2}\frac{|y_{L_i}|^2 f_a^2}{M_L^2} l_i^\dagger \bar{\sigma}_\mu l_i \partial_\mu a/f_a$$
$$-\frac{1}{2}\frac{|y_{E_i}|^2 f_a^2}{M_E^2} e_i^\dagger \bar{\sigma}_\mu e_i \partial_\mu a/f_a$$
$$+\frac{\alpha_s}{8\pi f_a} a G\tilde{G} + \frac{\alpha_2}{8\pi f_a} a W\tilde{W} + \frac{\alpha_1}{8\pi f_a} a B\tilde{B}$$

Field	$SU(3)_c$	$SU(2)_w$	$U(1)_Y$	$U(1)_{\rm PQ}$
L_i	1	$\square$	$+1/2$	-1
L_i^c	1	$\square$	$-1/2$	$+1$
E_i	1	1	-1	-1
E_i^c	1	1	$+1$	$+1$
Q	$\square$	$\square$	$+1/\sqrt{2}$	$-1/2$
Q^c	$\bar{\square}$	$\square$	$-1/\sqrt{2}$	$-1/2$
Φ	1	1	0	$+1$
l_i	1	$\square$	$-1/2$	0
e_i	1	1	$+1$	0

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