

Heavy QCD axions via dimuon final states

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S. Kumar, R. Co, [2210.02462 \(JHEP02\(2023\)111\)](#)
and with ArgoNeuT Collaboration, [2207.08448](#)



When we talk about Axion-Like-Particles (ALPs)...

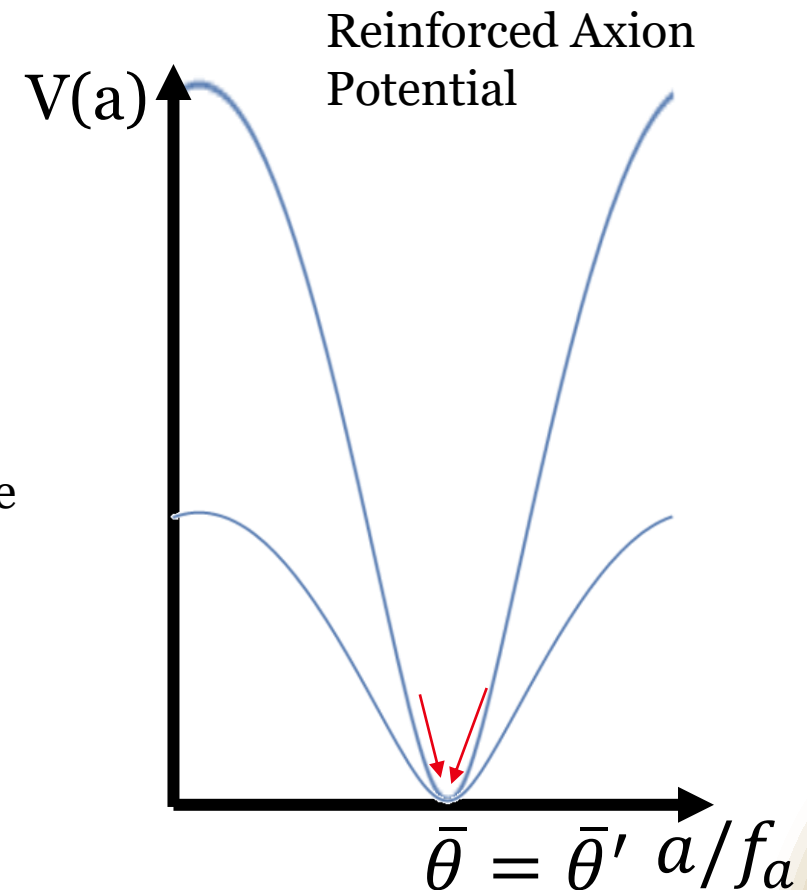
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When we talk about Axion-Like-Particles (ALPs)...

- In the particle realm, we most of the time just talked about a pseudo scalar...
- But the defining coupling is to gluons, to make some connections to strong CP. Can we motivate that?

Reinforce Axion potential (also Solves Quality Problem)

Use mirror QCD dimensional transmutation to generate large mirror QCD scale

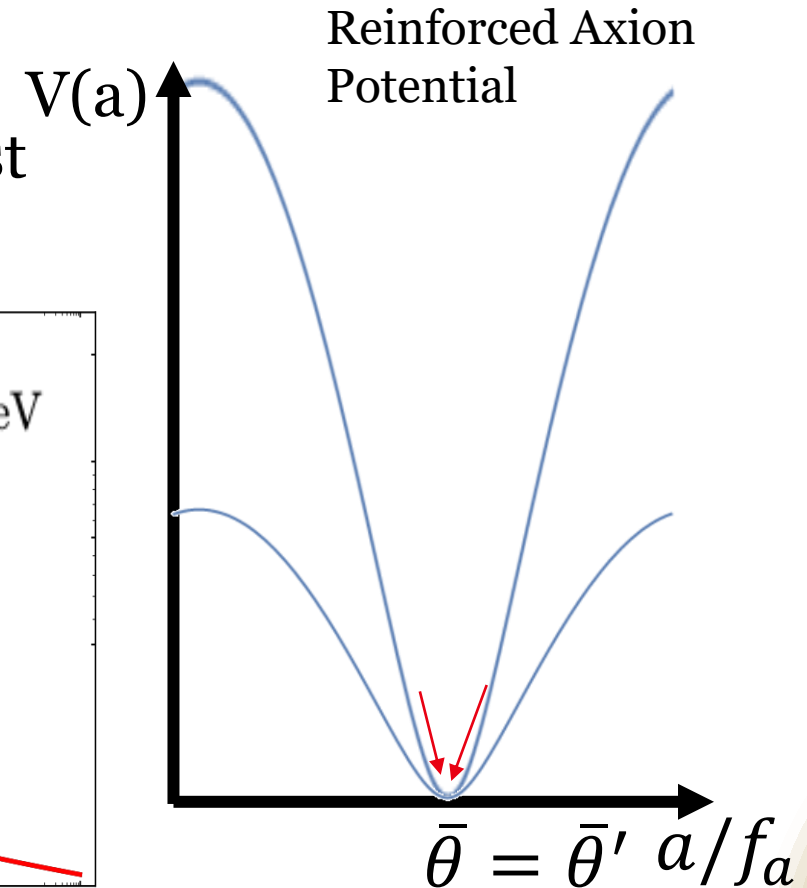
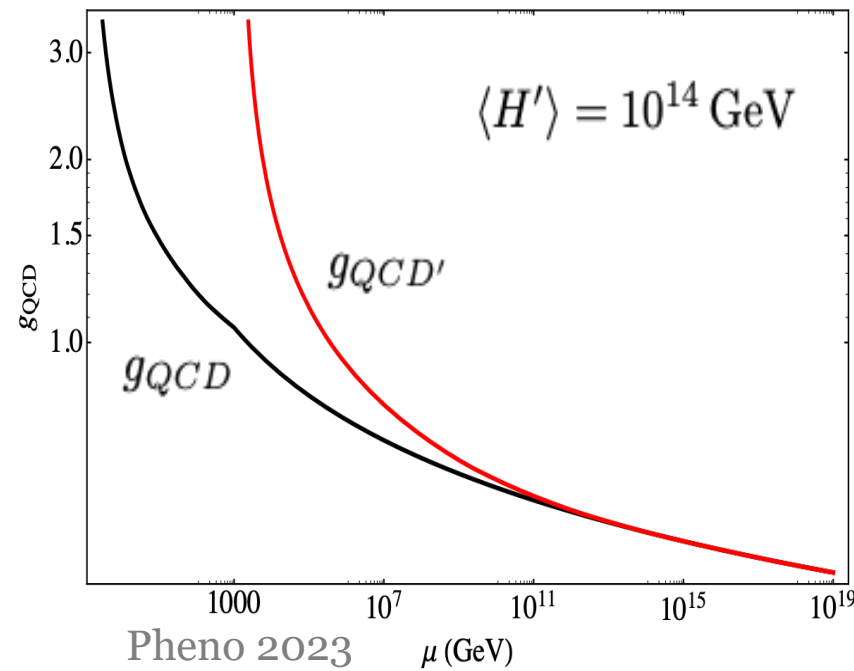


Hook, Kumar, ZL, Sundrum,
[1911.12364](#)

Also see related: Rubakov, 97' Hook, 14'
Dimopoulos, Hook, Huang, Marques-Tavares, 16'
Gherghetta, Nagata, Shifman, 16' Argarwal, Howe,
17' Csaki, Ruhdorfer, Shirman, 19' Gherghetta,
Khoze, Pomarol, Shirman, 20', and many more...

Reinforce Axion potential (also Solves Quality Problem)

Soft Z₂ breaking by giving
Mirror Higgs large VEV
→ massive fermions
decouples earlier
→ mirror QCD runs fast
and confines



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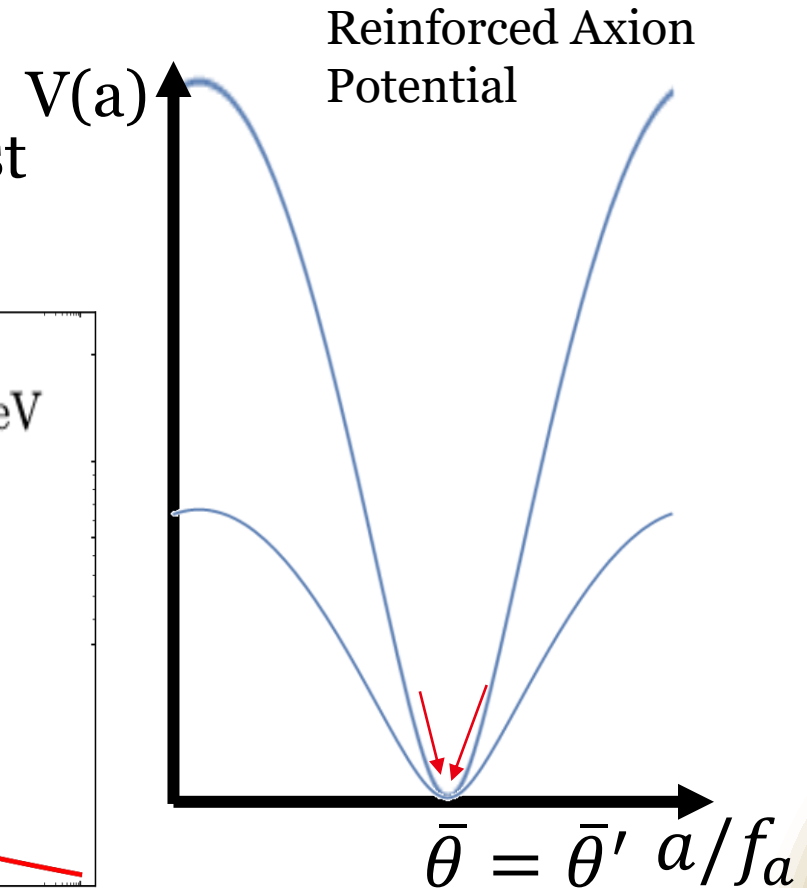
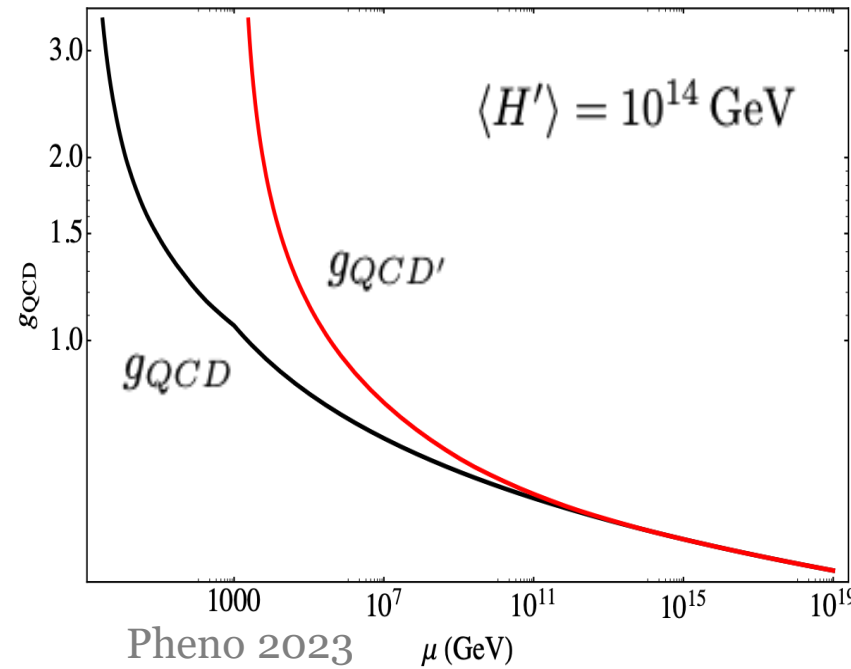
Reinforce Axion potential (also Solves Quality Problem)

$$m_a^2 \simeq \frac{m_u m_d}{(m_u + m_d)^2} \frac{m_\pi f_\pi}{f_a^2}$$



$$m_a^2 \simeq \frac{\Lambda_{QCD'}^4}{f_a^2}$$

Soft Z2 breaking by giving
Mirror Higgs large VEV
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One can look for dimuons (many experiments)

- 2μ decay can generically dominant

$$\mathcal{L}_{\text{gauge}} = \frac{c_3 \alpha_3}{8\pi f_a} a G \tilde{G} + \frac{c_2 \alpha_2}{8\pi f_a} a W \tilde{W} + \frac{c_1 \alpha_1}{8\pi f_a} a B \tilde{B}.$$

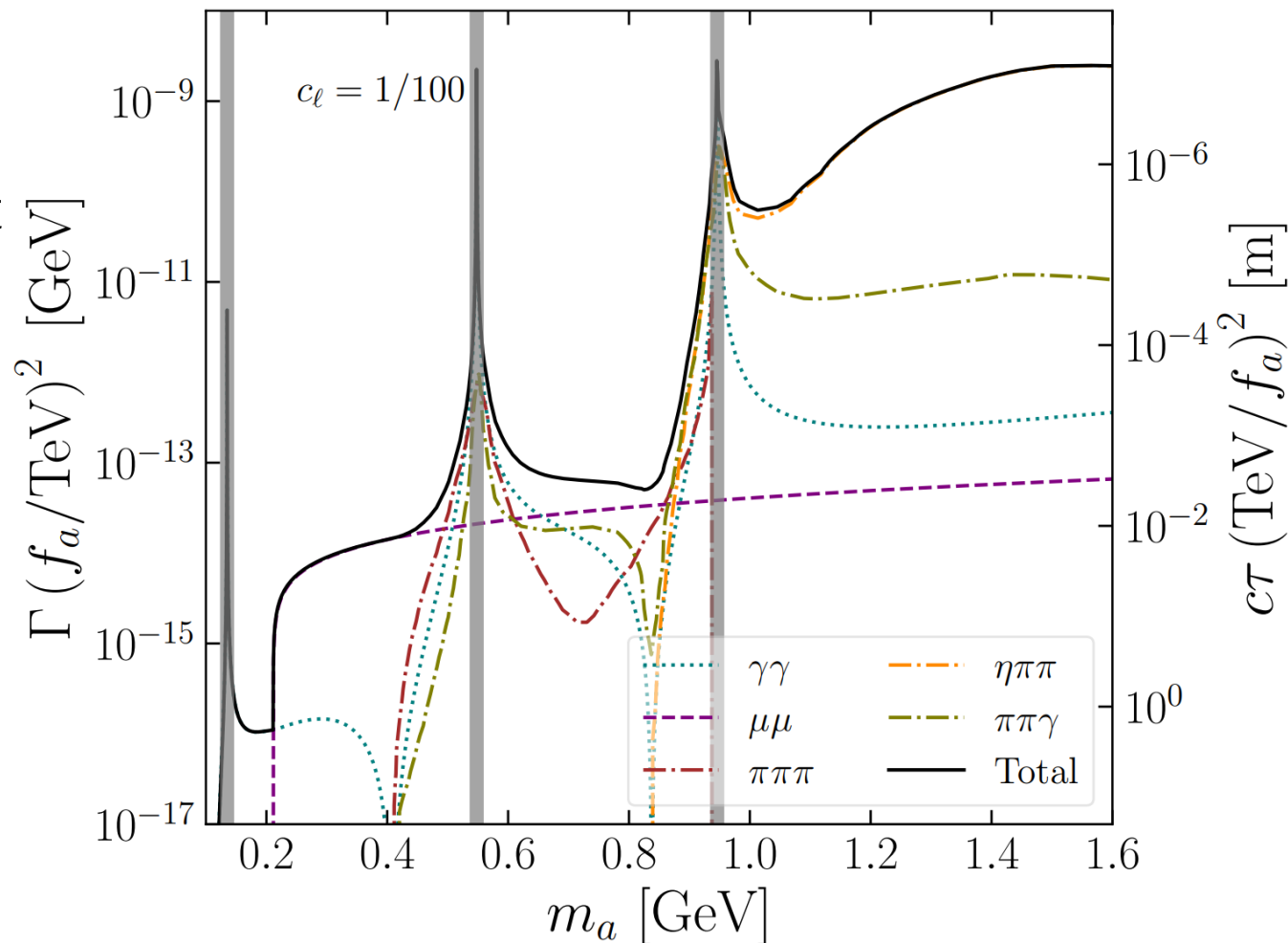
$$\mathcal{L}_{\text{lepton}} = \sum_{\ell=e,\mu,\tau} \frac{\partial_\mu a}{2f_a} (c_{V\ell} \bar{\ell} \gamma^\mu \ell + c_{A\ell} \bar{\ell} \gamma^\mu \gamma_5 \ell)$$

Originated from UV structure
(vector-like leptons)

$$c_\ell \simeq (0.05c_1 + 0.22c_2 + 0.37c_3) \times 10^{-3}$$

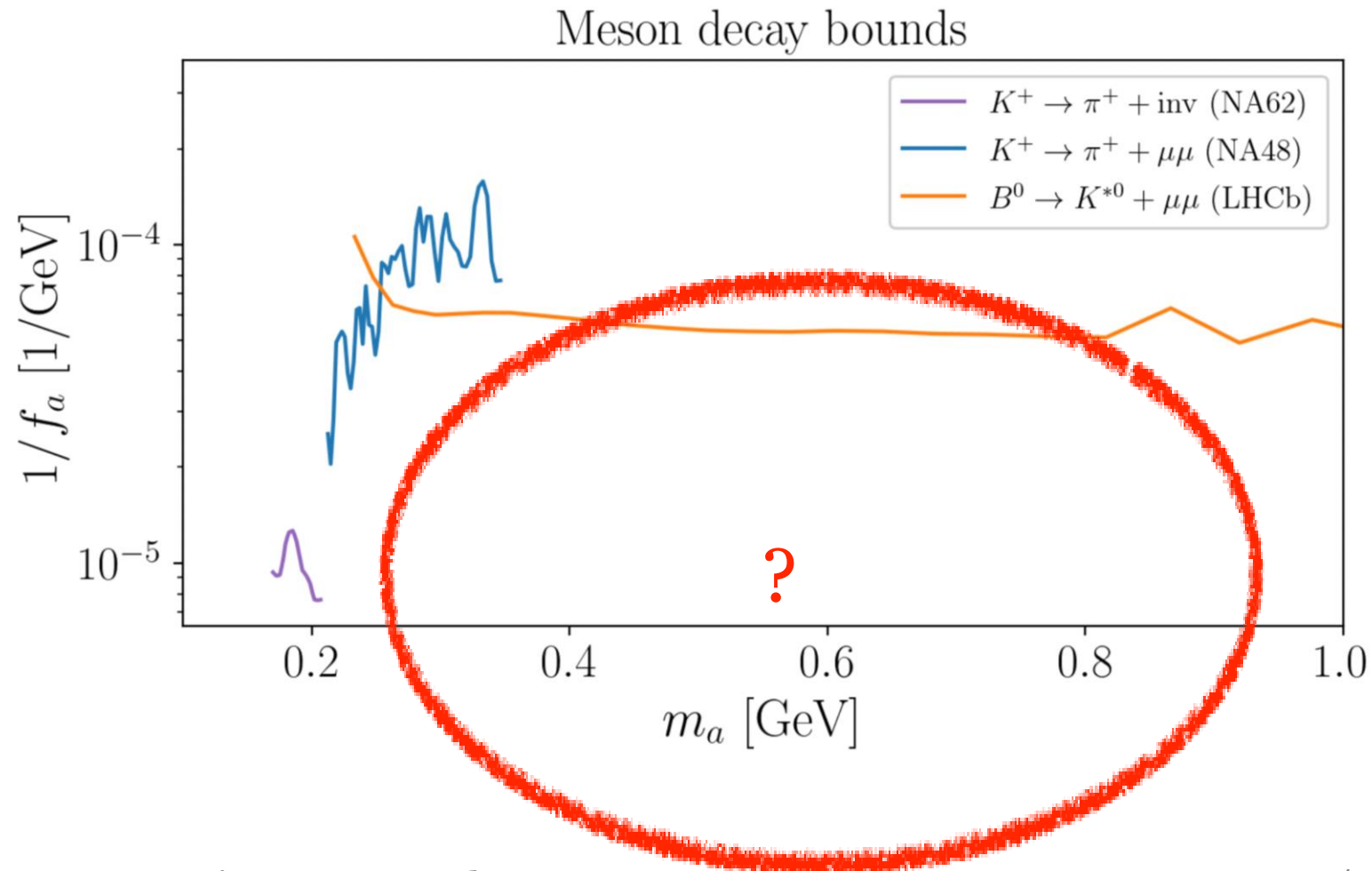
One can also radiatively
generate leptonic couplings

(see coefficient matching calculation
Bauer, Neubert, Renner, Schnubel,
Thamm, 2012.12272)

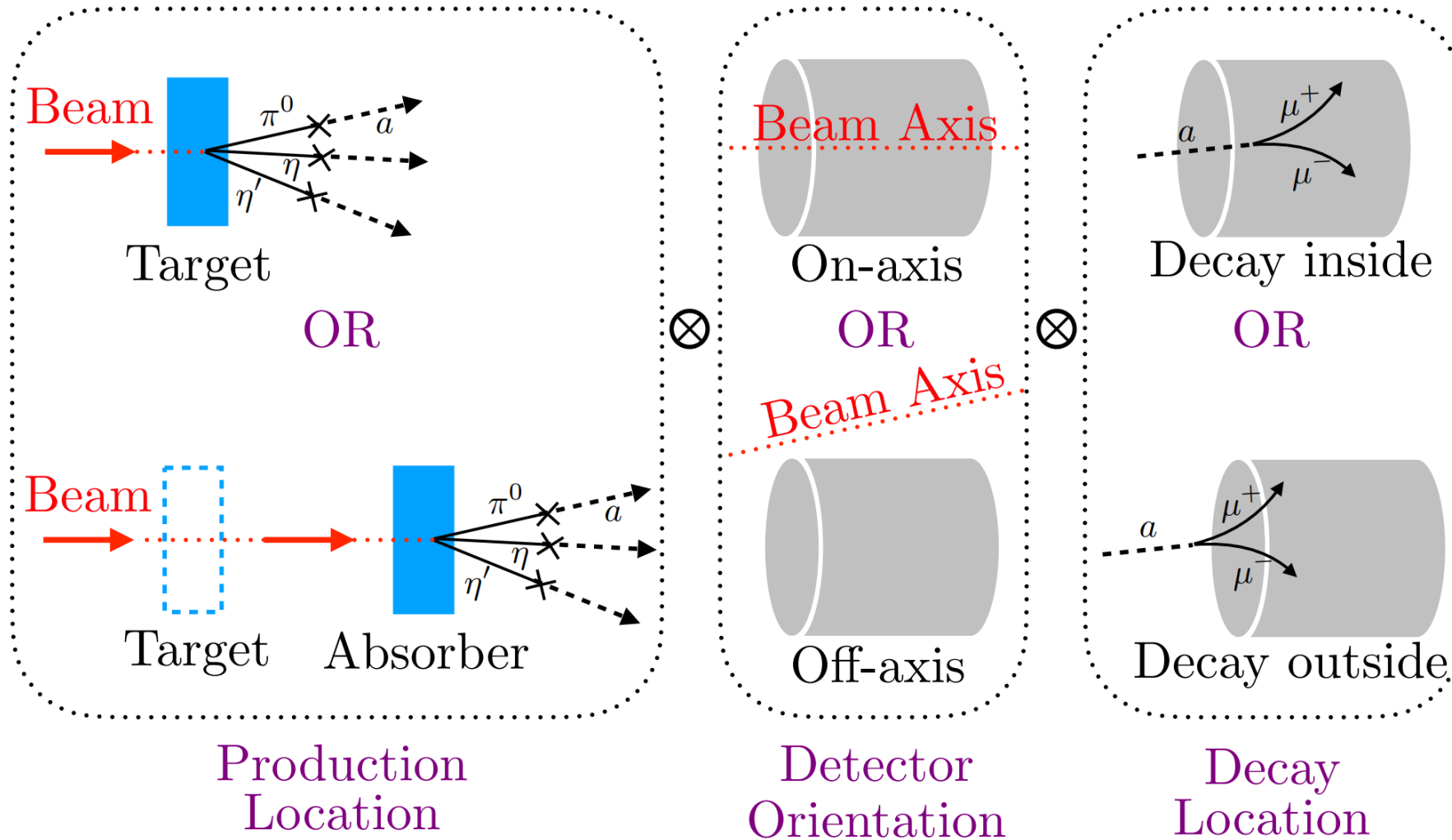


Constraints

- Renormalization group evolution induces **flavor off-diagonal quark couplings**, and constraints from rare meson decay



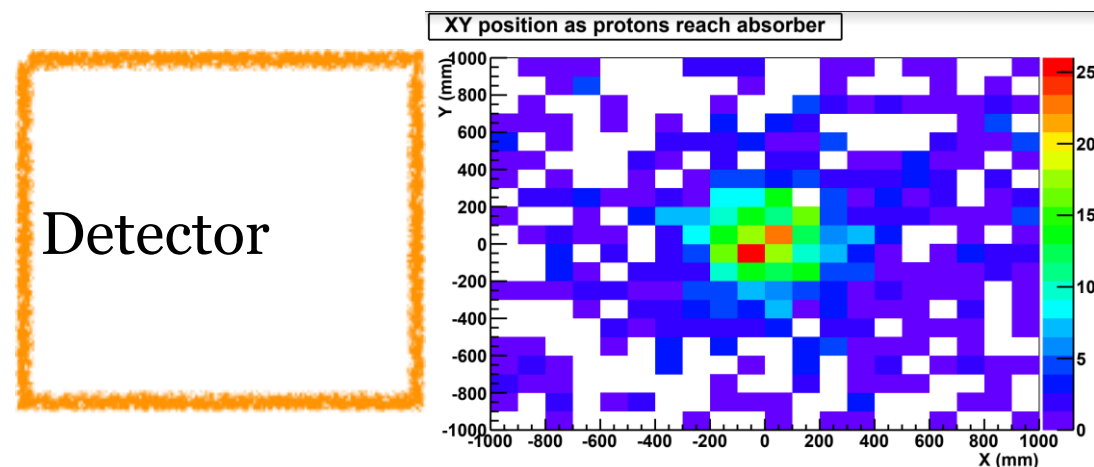
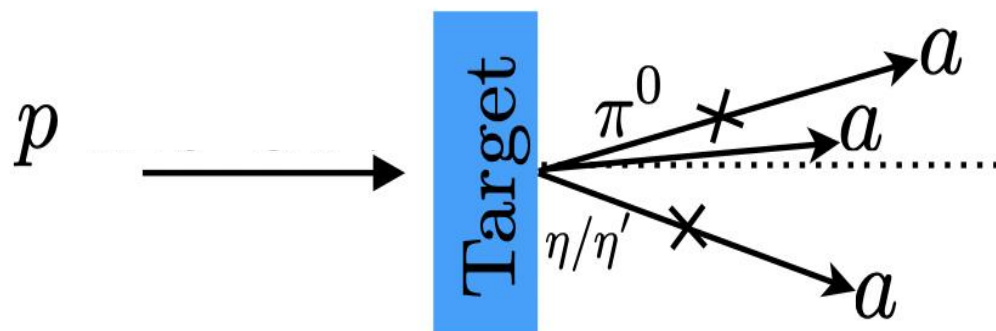
Beamdump Possibilities & Complexities:



Many Beamdumps Available

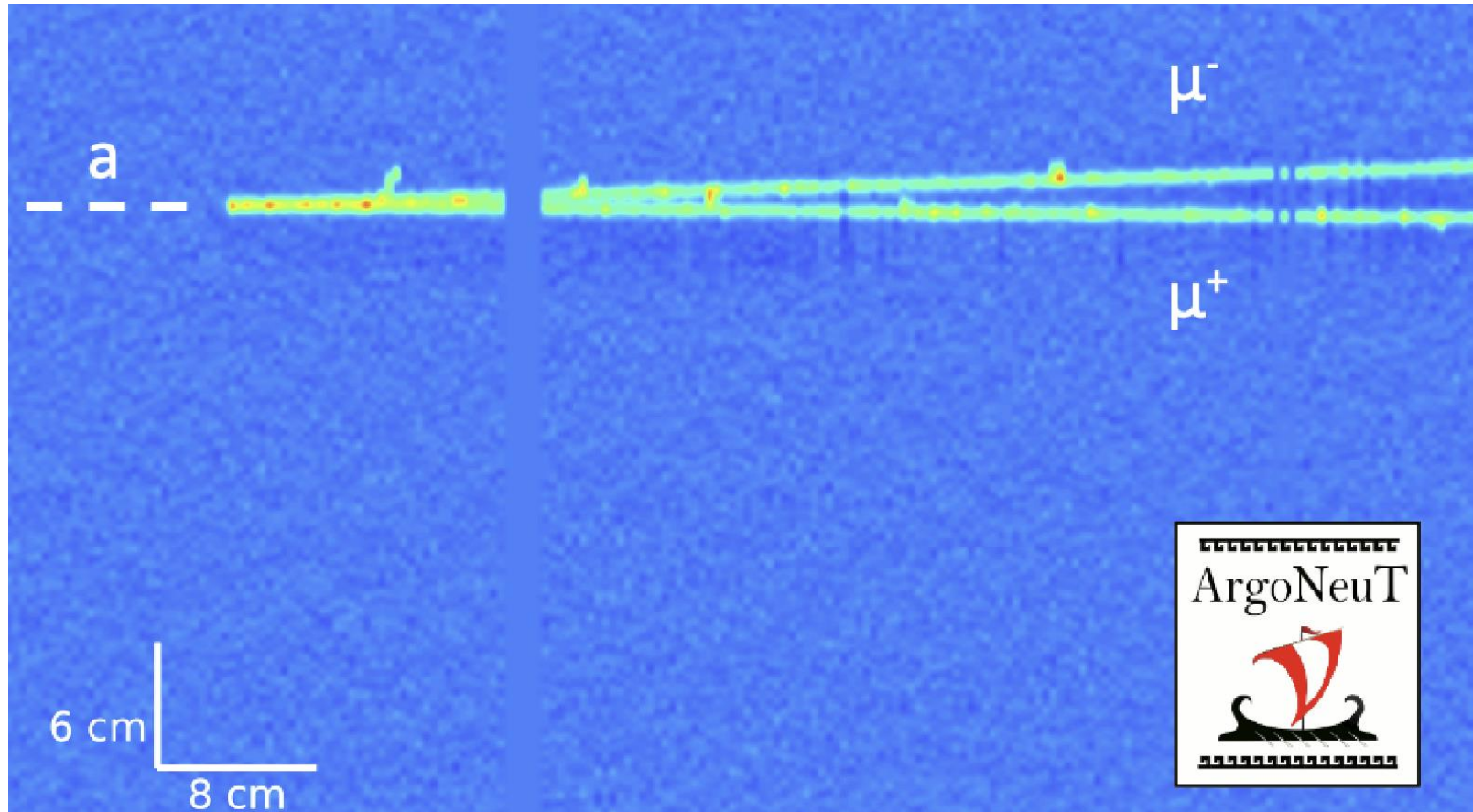
Experiments	E_p (GeV)	N_{POT}	d (m)	L (m)	$w \times h$ (m×m)
DUNE [124, 125]	120	1.47×10^{22}	574	5 + 5	7×3 ($r_{\text{eff}} = 2.6$ m)
SBND [126] $\begin{cases} \text{BNB} \\ \text{NuMI} \end{cases}$	8	6.6×10^{20}	110	5	4×4 ($r_{\text{eff}} = 2.3$ m)
	120	3×10^{21}	410		
MicroBooNE [126, 127] $\begin{cases} \text{BNB} \\ \text{NuMI} \end{cases}$	8	1.32×10^{21}	470	10.4	2.6×2.3 ($r_{\text{eff}} = 1.4$ m)
	120	3×10^{21}	685		
ICARUS [126] $\begin{cases} \text{BNB} \\ \text{NuMI} \end{cases}$	8	6.6×10^{20}	600	19.9	$(3.9 \times 3.6) \times 2$ ($r_{\text{eff}} = 2.1$ m)
	120	2.5×10^{21}	790		
SHiP [128]	400	2×10^{20}	70	50	5×10 ($r_{\text{eff}} = 4.0$ m)
FASER 2 [95, 96]	14000	1.1×10^{16} (LHC Run 3) 2.2×10^{17} (HL-LHC)	480	5	$r = 1$ m

Production



$$N_{\text{axions}} = N_{\text{POT}} \times \begin{cases} 0.82|\theta_{a\pi}|^2 + 0.072|\theta_{a\eta}|^2 + 0.0038|\theta_{a\eta'}|^2 & \text{for 8 GeV BNB} \\ 2.9|\theta_{a\pi}|^2 + 0.33|\theta_{a\eta}|^2 + 0.034|\theta_{a\eta'}|^2 & \text{for 120 GeV NuMI beam} \\ 4.0|\theta_{a\pi}|^2 + 0.46|\theta_{a\eta}|^2 + 0.049|\theta_{a\eta'}|^2 & \text{for 400 GeV SPS beam} \\ 33|\theta_{a\pi}|^2 + 3.8|\theta_{a\eta}|^2 + 0.48|\theta_{a\eta'}|^2 & \text{for 14 TeV LHC} \end{cases}$$

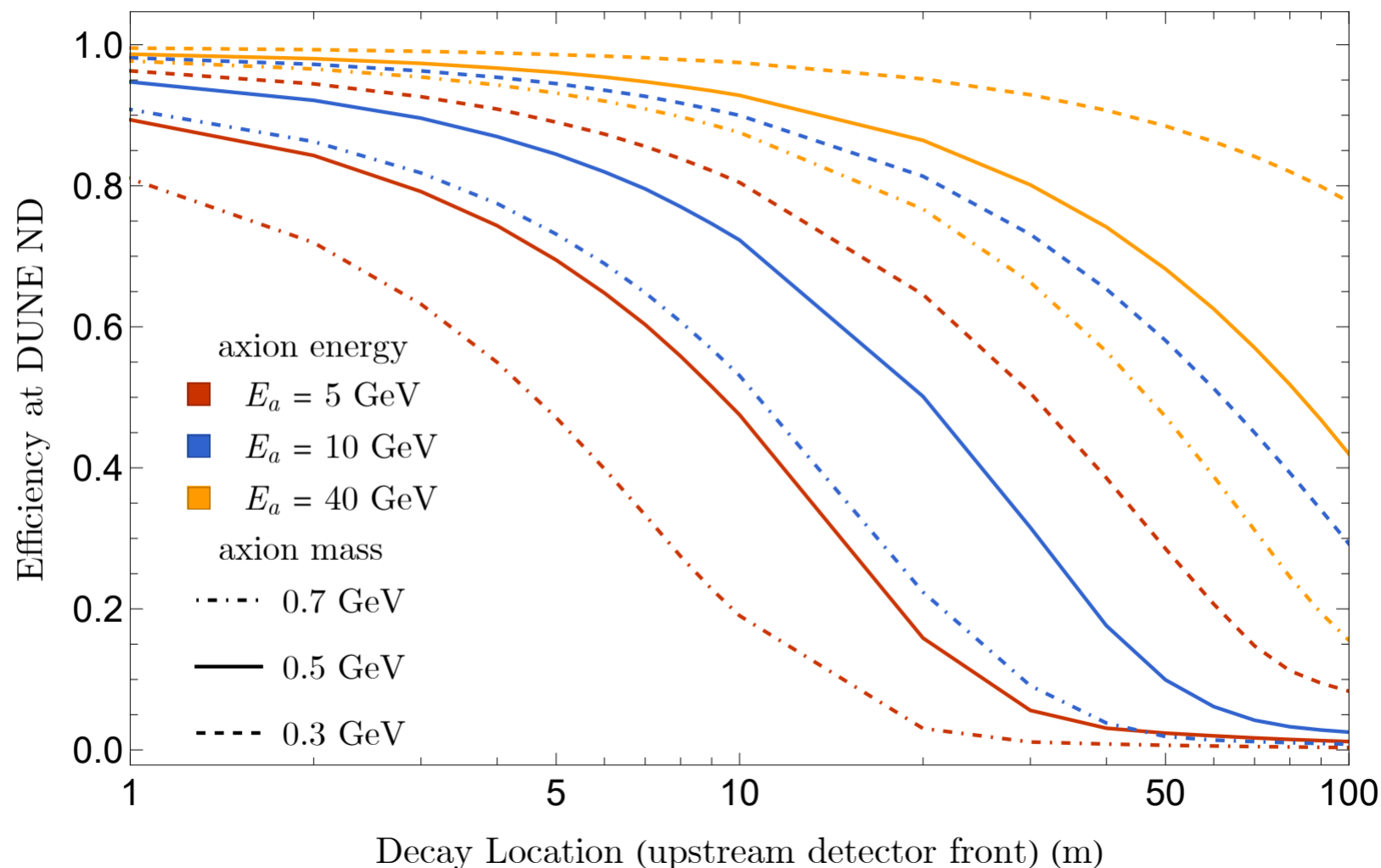
Decay outside the detectors can also be spotted



One can effectively enhance the detector length by another **10-30 meters** without much loss of signal efficiency (here, we required both muons to get into the active detector volume).

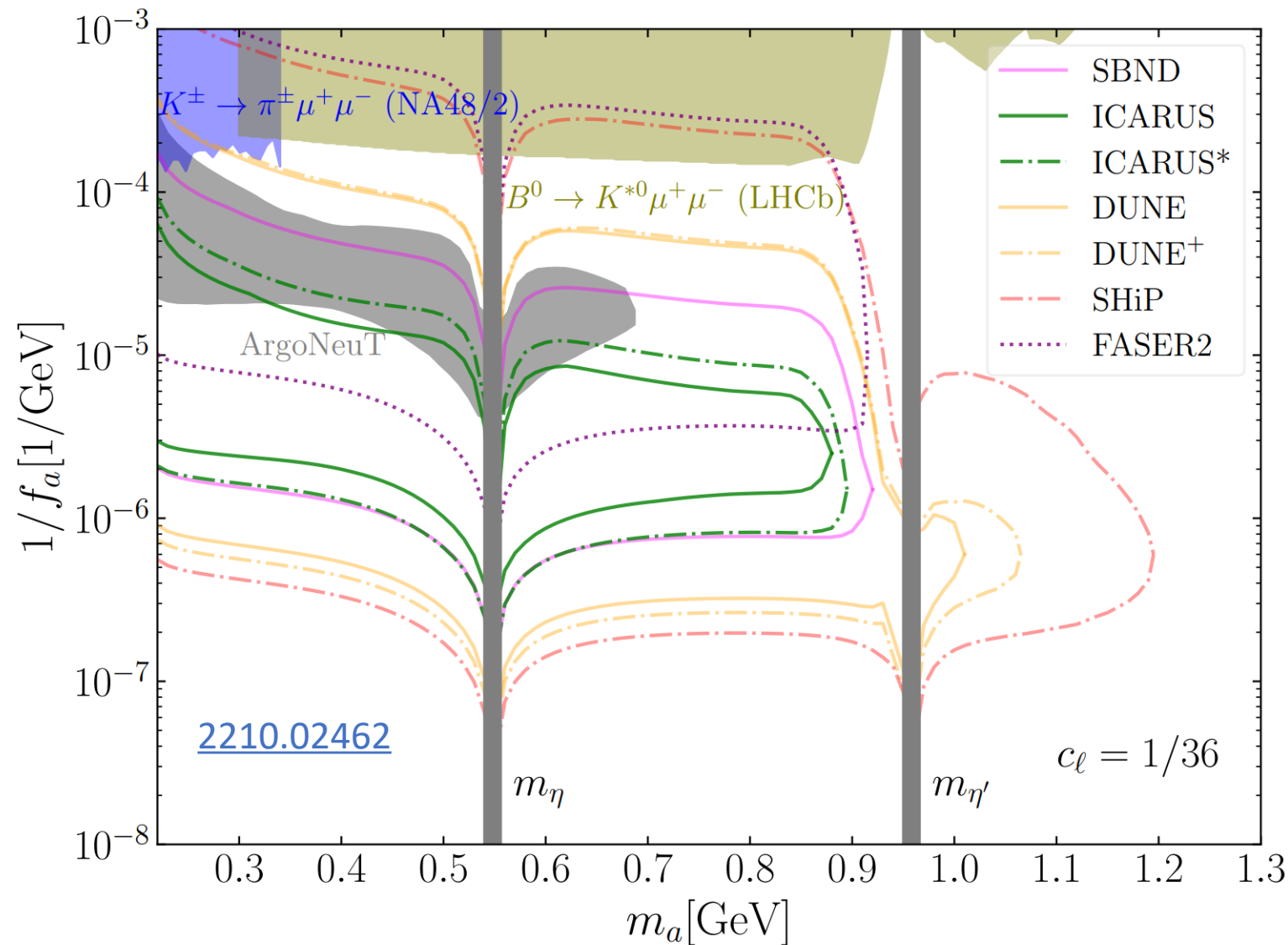
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$a \rightarrow \mu\mu$ reaching >1m downstream detector front



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Results and Projections



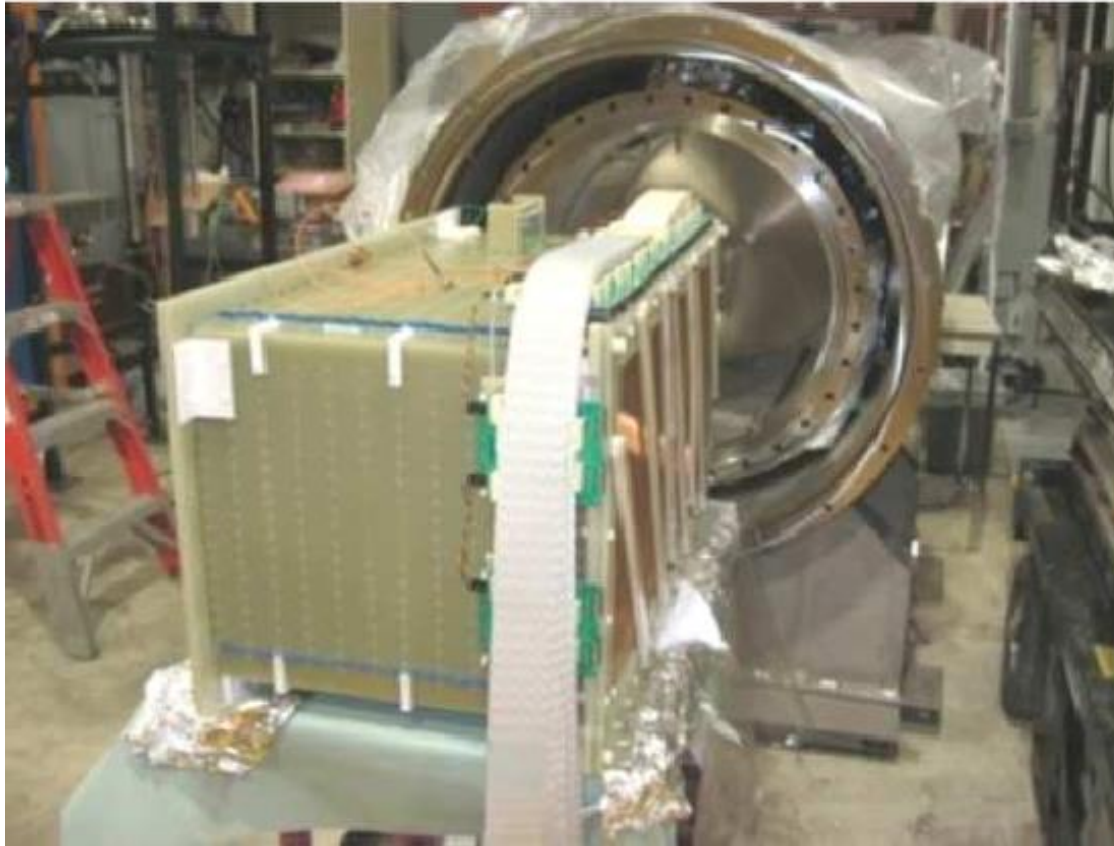
Many new parameter spaces can be probed by various future experiments:

- One order of magnitude in mass
- Three-four orders of magnitude in coupling.

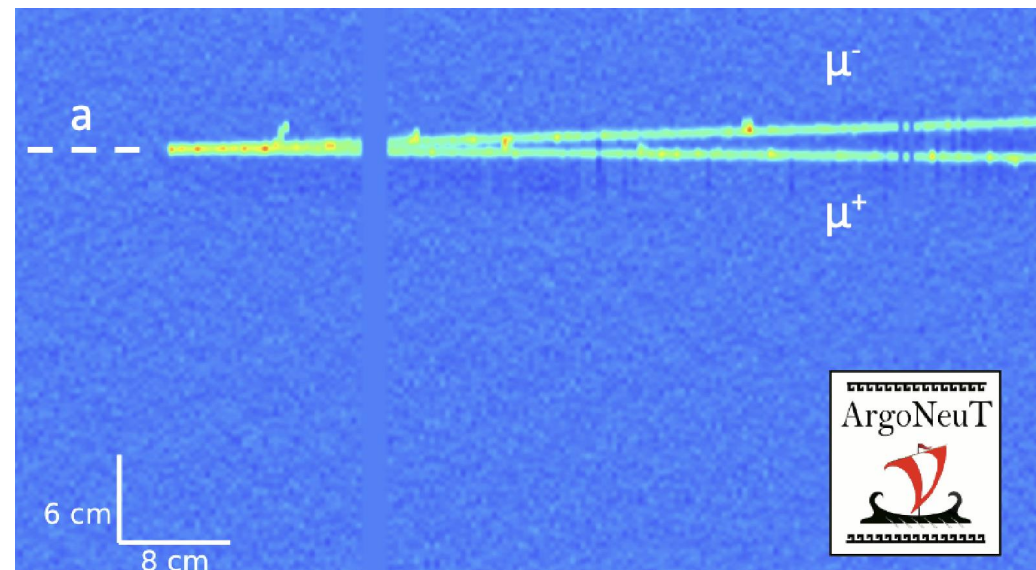
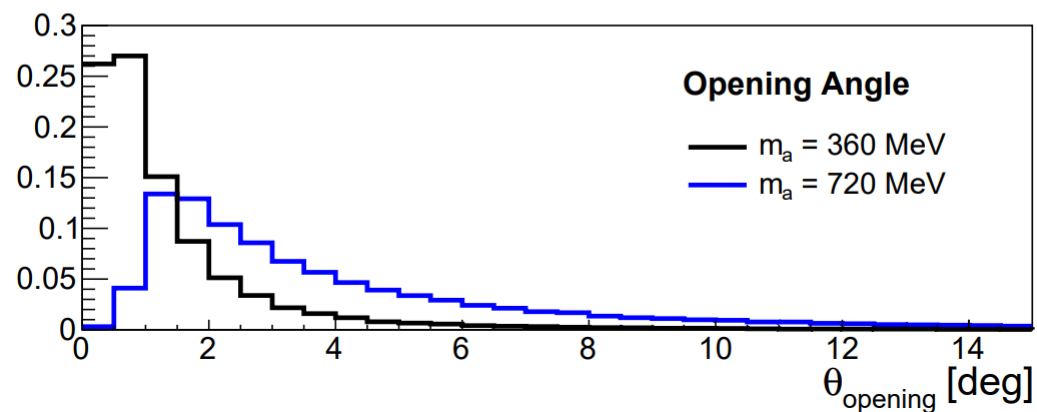
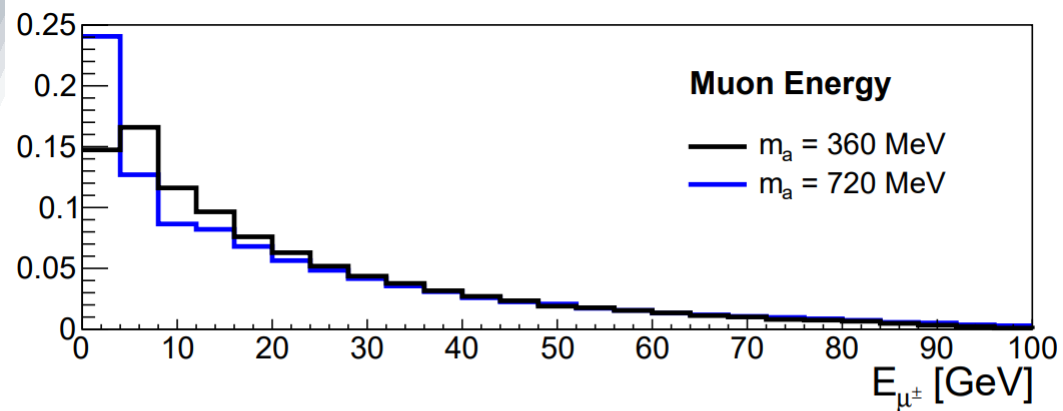
In particular, we demonstrate the impact of including

- Off-axis data (with the example of ICARUS*)
- Decays before detector (with the example of DUNE+)

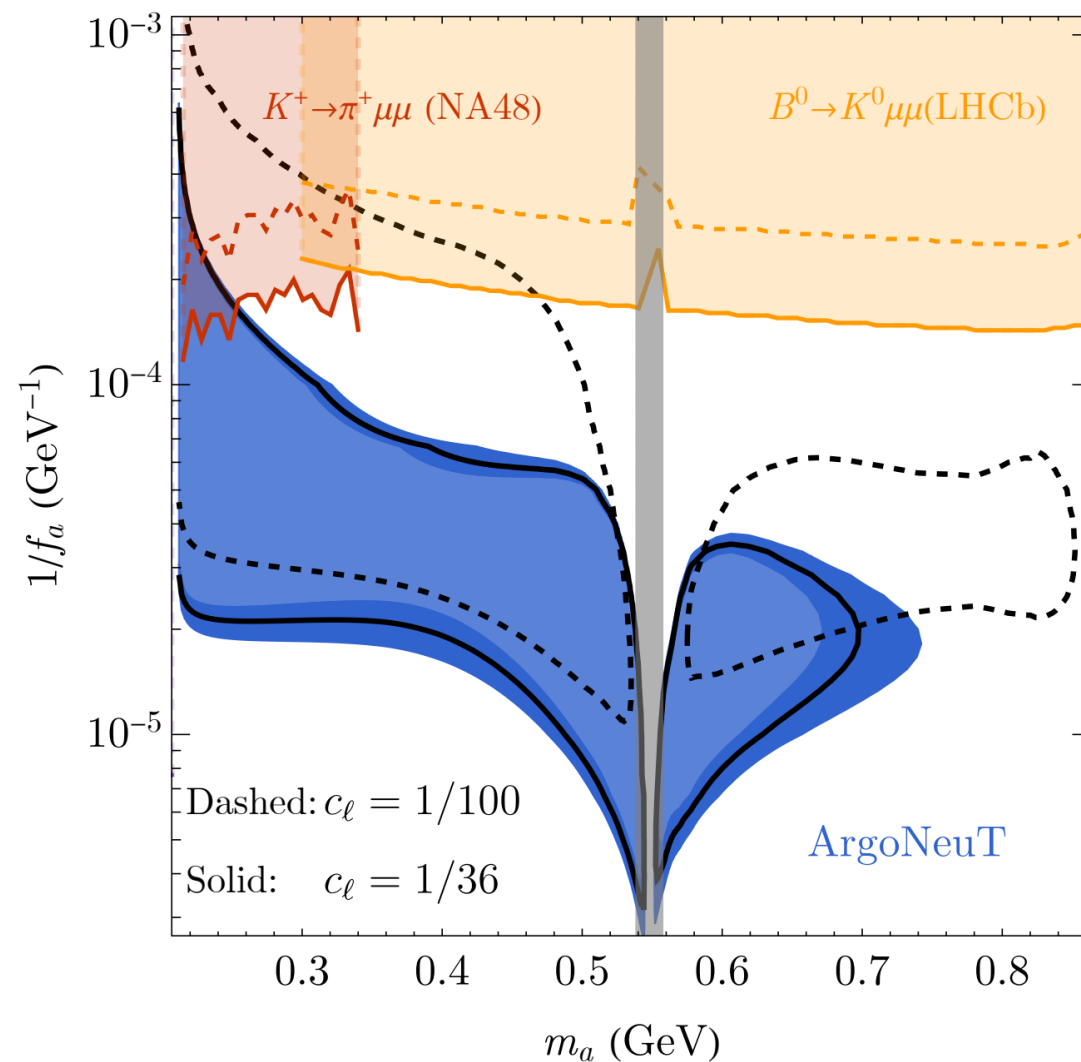
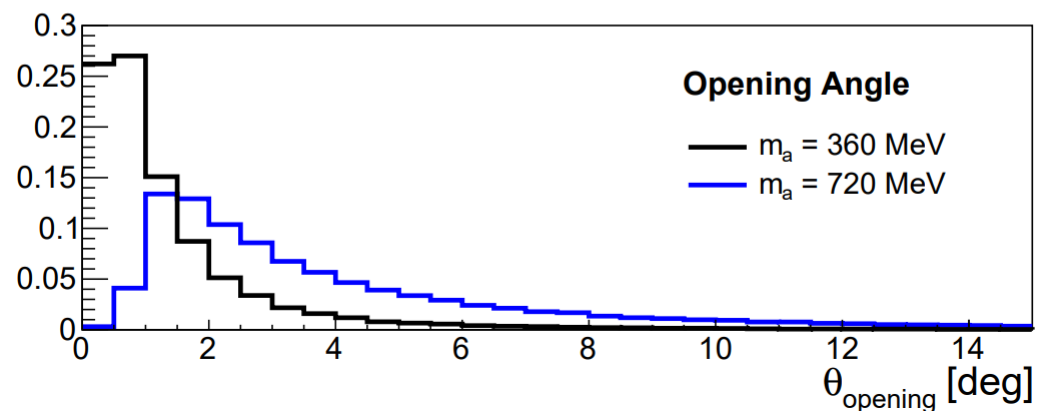
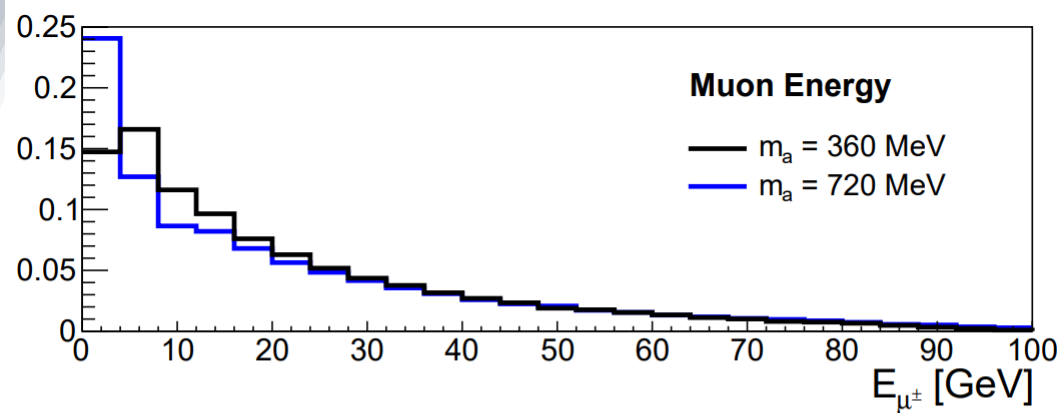
Can we do something with the existing data?



ArgoNeuT Result

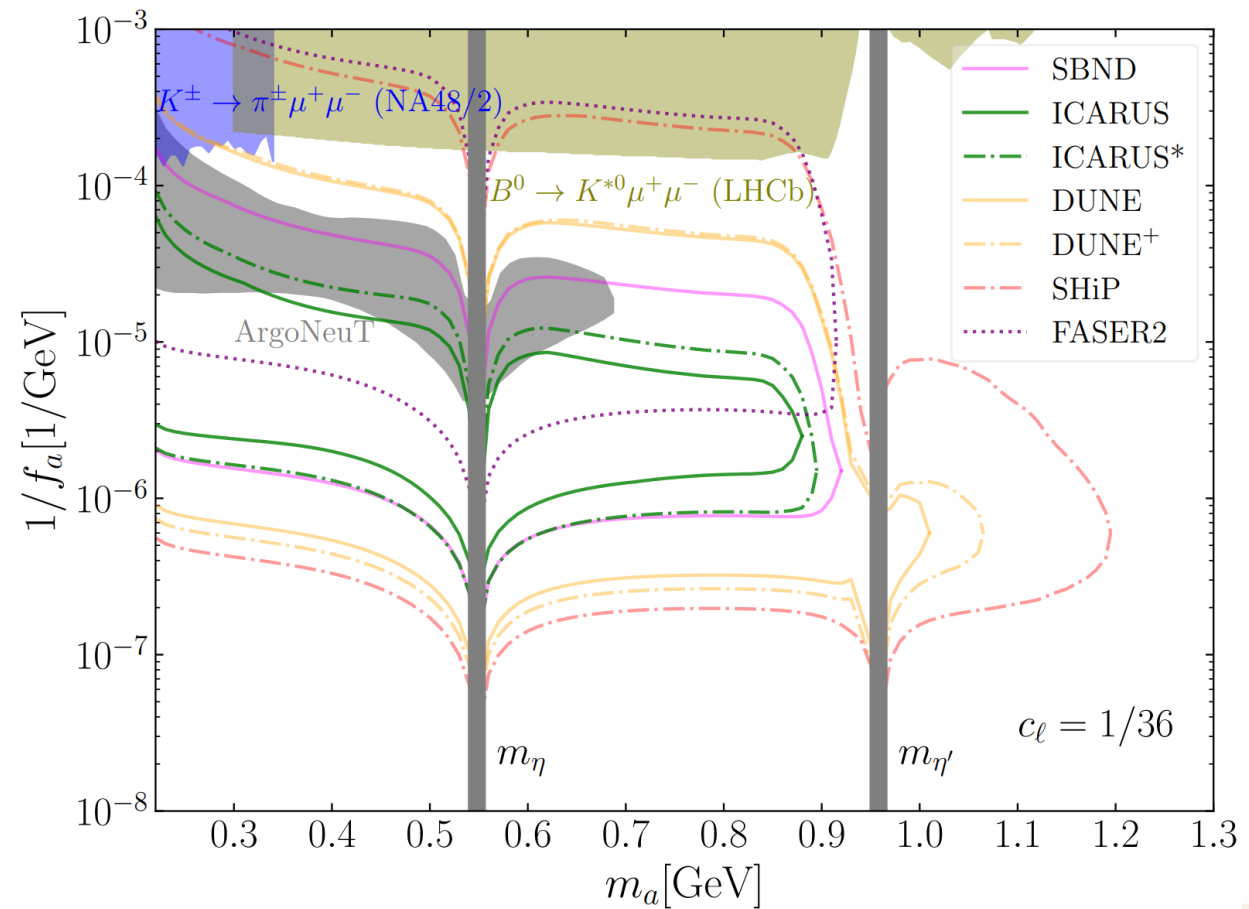


ArgoNeuT Result



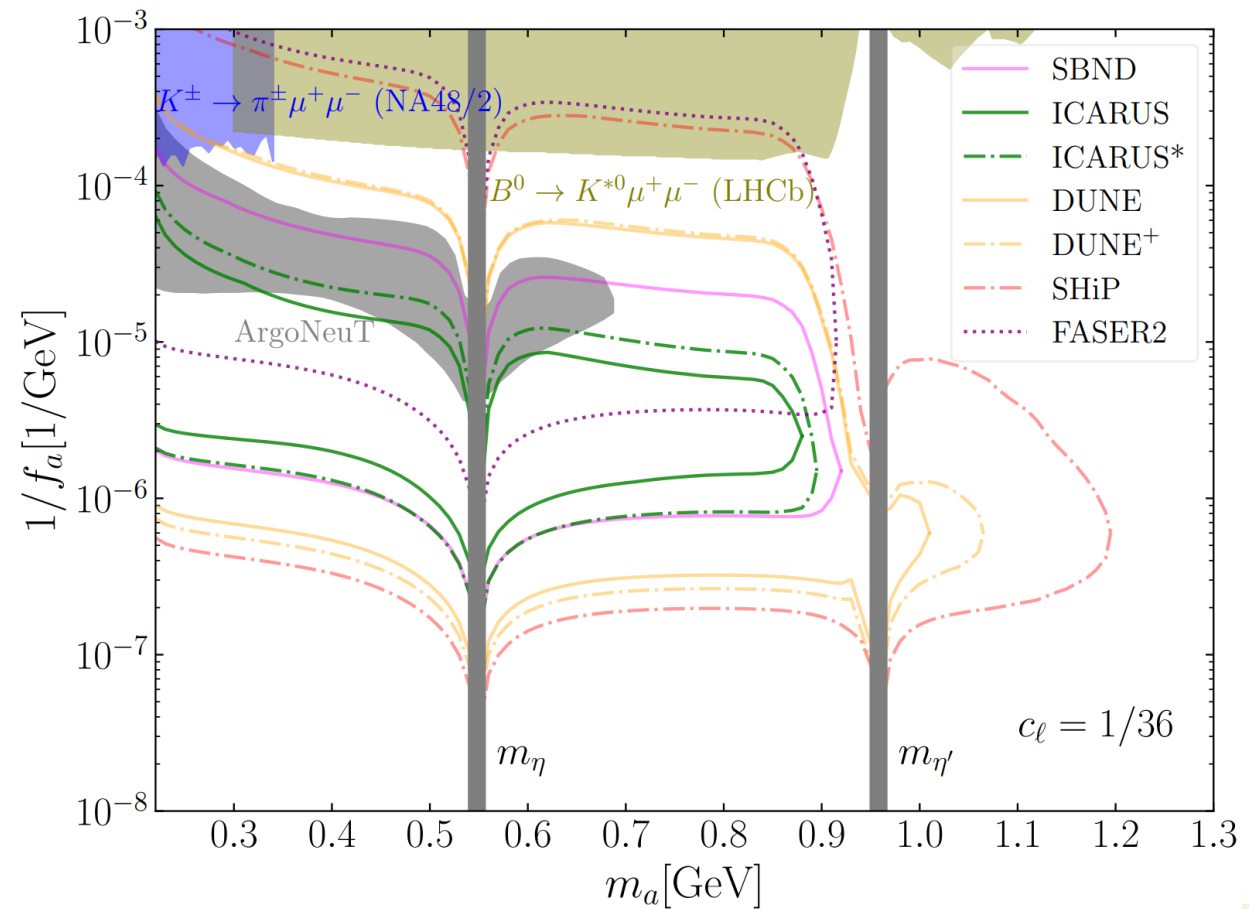
Summary

- Gluonic ALPs are interesting to search for;
- Can be motivated by strong CP and the quality problem
- Its production, decay, and search strategy all have interesting features/improvements to explore.
- The Dimuon final states are particularly interesting as we have many ongoing and planning experiments, and new search opportunities emerge for such well-motivated scenarios.



Summary

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Thank you!

Example of UV completion

Field	$SU(3)_c$	$SU(2)_L$	$U(1)_Y$	$U(1)_{PQ}$
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

$$c_\ell \simeq (0.05c_1 + 0.22c_2 + 0.37c_3) \times 10^{-3}$$

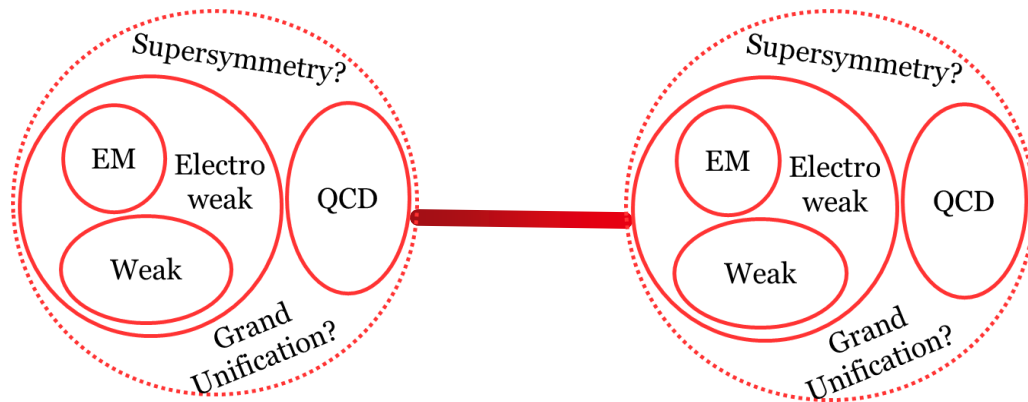
$$\mathcal{L} \supset y_{L_i} L_i l_i \Phi + y_{E_i} E_i e_i \Phi + y_Q Q Q^c \Phi + M_L L_i L_i^c + M_E E_i E_i^c + \text{h.c.}$$

$$c_\ell = \frac{1}{2} \left(\frac{|y_{L_i}|^2 f_a^2}{M_L^2} + \frac{|y_{E_i}|^2 f_a^2}{M_E^2} \right)$$

The Quality Problem and reinforced Axion potential

Copying Mirror Gauge QCD + Weak and Chiral Matter fields, relates the Lagrangian parameters with a Z_2 symmetry

one axion couples to both and **solve both** strong CP puzzles dynamically.



$$\begin{aligned} SU(2) &\leftrightarrow SU(2)' \\ SU(3) &\leftrightarrow SU(3)' \\ U(1) &\leftrightarrow U(1)' \text{ or } U(1) \leftrightarrow U(1) \\ \Psi &\leftrightarrow \Psi' \end{aligned}$$

\leftrightarrow represents the Z_2 transformation
 X' represents the mirror sector

Softly broken by
 $\mu^2 H^\dagger H + \mu'^2 H'^\dagger H'$
 with $|\mu'^2| \gg |\mu^2|$

Rubakov '97, Berezhiani et al '01, Hook '15, Fukuda et al '15...