UC-Davis

QMAP Particles/Cosmology Seminar

Hunting for Gluonic 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?

Axion needs no intro

$$L \supset \frac{\alpha_s}{8\pi}\theta\tilde{G}G + y_u\bar{Q}_L\tilde{H}u_R + y_d\bar{Q}_L H d_R$$

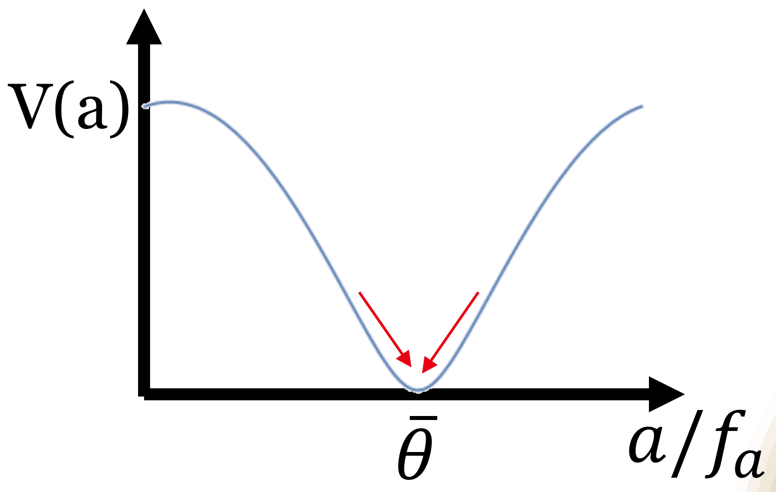
$$\bar{\theta} \equiv \theta + \mathrm{ArgDet}[Y_u Y_d] \leq 10^{-10}$$

While ArgDet$[Y_u Y_d]$ anticipated around $\delta_{CKM} \sim O(1)$

Strong CP puzzle of QCD

Dynamical solution:
QCD Axion a as a pseudo Nambu-Goldstone boson

$$\frac{\alpha_s}{8\pi}\left(\theta - \frac{a}{f_a}\right)\tilde{G}G$$



But a quality problem

The axion fakes a dynamical angle.
How good of an imposter is it?

Dynamical solution:
QCD Axion a as a pseudo Nambu-Goldstone boson

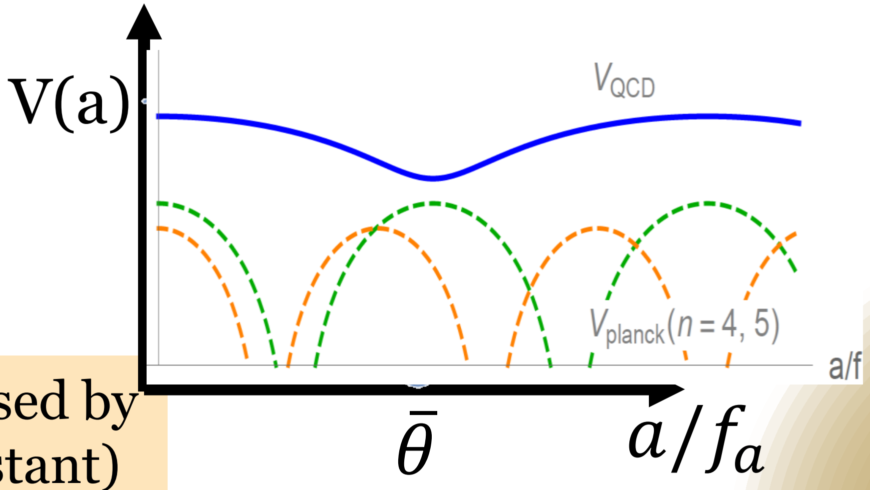
$$V \approx -(100\,\mathrm{MeV})^4 \cos\left(\bar{\theta} - \frac{a}{f_a}\right) + \Lambda^4_{\mathrm{contamination}} \cos\left(\theta' - \frac{a}{f_a}\right)$$

$$\frac{\alpha_s}{8\pi}\left(\theta - \frac{a}{f_a}\right)\tilde{G}G$$

$$\Lambda_{\mathrm{contamination}} < 0.1\,\mathrm{MeV}$$

There are also many other scales :
GUT, Planck, Dark matter

$$V = \frac{\Phi^{14}}{M_{pl}^{10}} \qquad \Phi \equiv e^{i\frac{a}{f_a}}$$



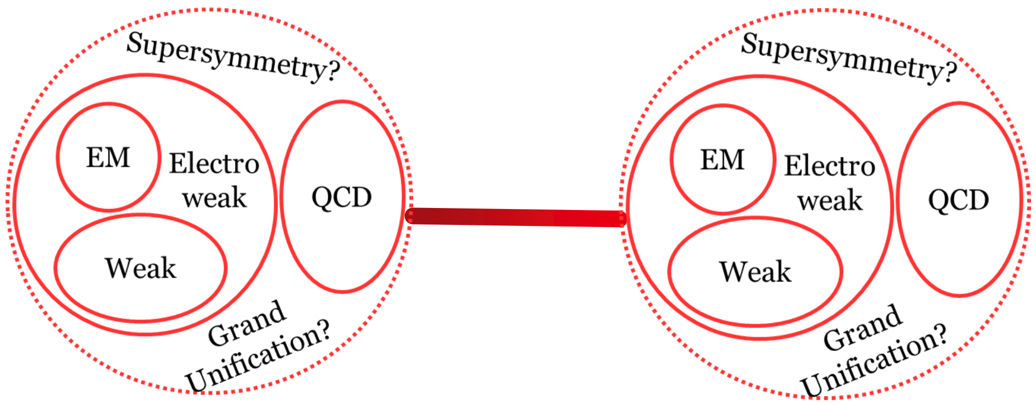
Leading order gravity suppressed operators need to be suppressed by 10 powers of the Planck scale! (for 10^12 GeV Axion decay constant)

Other solutions (while not excluded by experiments) to the axion quality problem exists, e.g., delicate UV structure, Extra dimensions, etc.

Hook, Kumar, ZL, Sundrum, 1911.12364

The Quality Problem and reinforced Axion potential

Copying Mirror Gauge QCD + Weak and Chiral Matter fields, relates the Lagrangian parameters with a Z2 symmetry
one axion couples to both and solve both strong CP puzzles dynamically.



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

$\leftrightarrow$ represents the Z2 transformation
X' represents the mirror sector

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

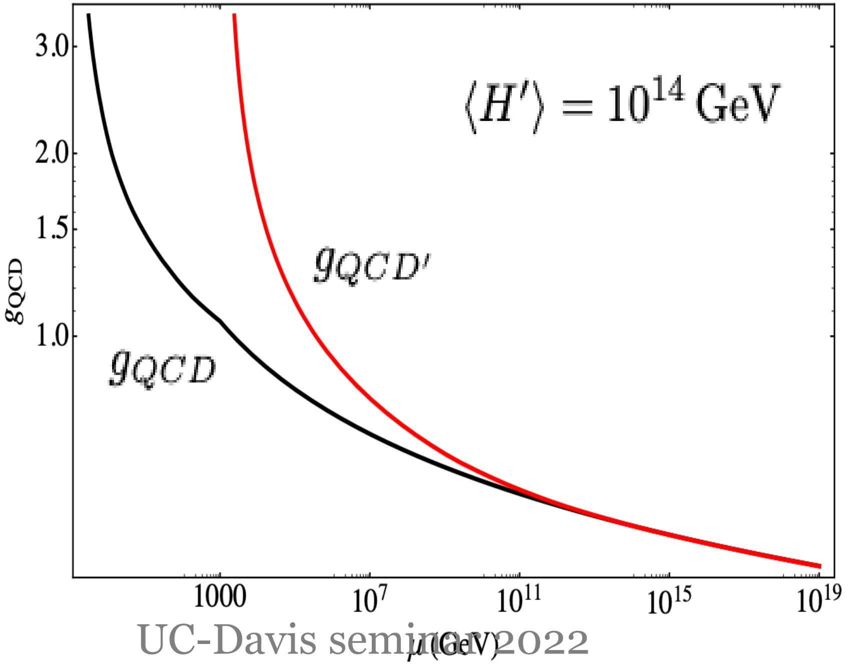
Rubakov '97, Berezhiani et al '01, Hook '15, Fukuda et al '15…

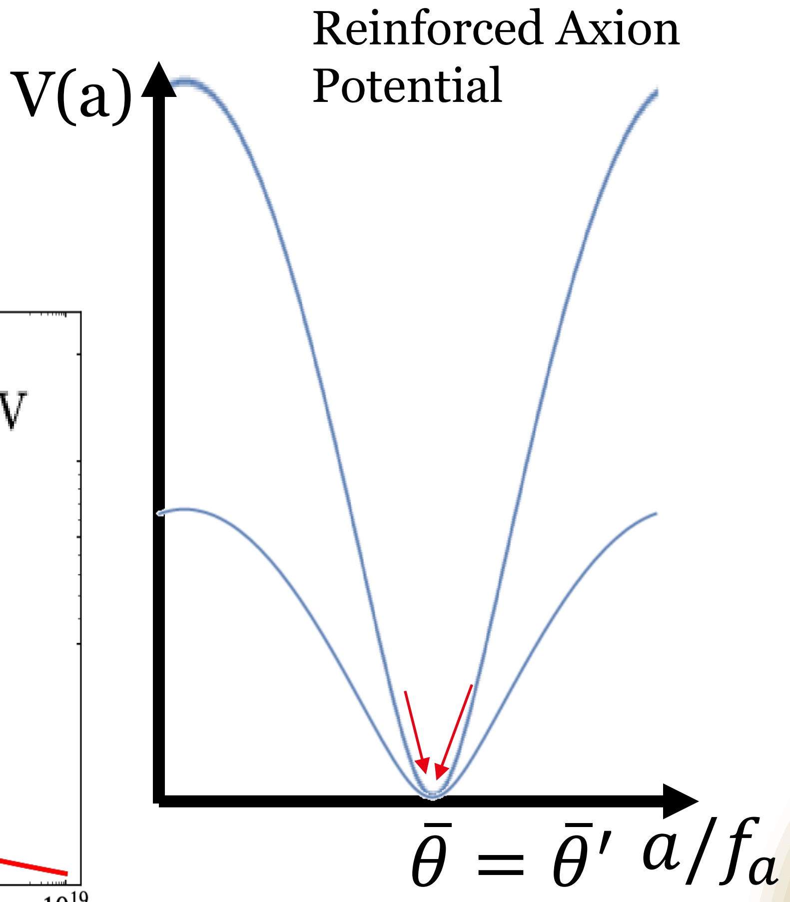
The Quality Problem and reinforced Axion potential

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

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

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



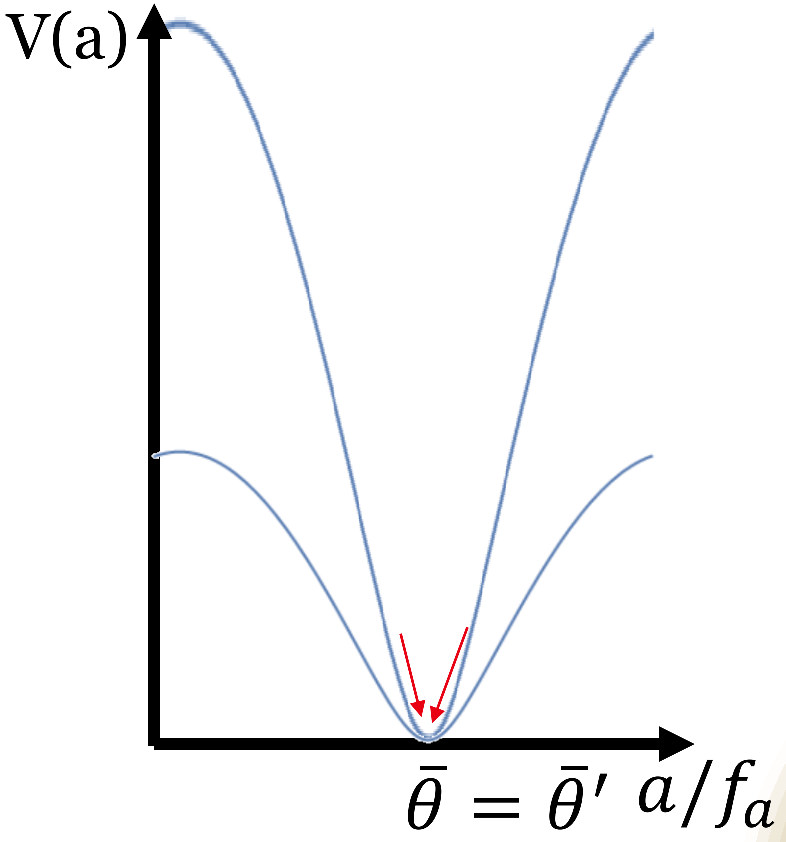


The Quality Problem and reinforced Axion potential

Makes the Quality problem better

$$V \approx -(100\,\mathrm{MeV})^4 \cos\left(\bar{\theta} - \frac{a}{f_a}\right) - (10^8\,\mathrm{MeV})^4 \cos\left(\bar{\theta} - \frac{a}{f_a}\right)$$
$$+\Lambda^4_{\mathrm{contamination}} \cos\left(\theta' - \frac{a}{f_a}\right)$$

$$\Lambda_{\mathrm{contamination}} < 10^5\,\mathrm{MeV}$$



If the Higgs mass were the only thing different between the two copies, the neutron angles are still the same!
Flavor structure of the SM ensures that any change occurs in very high loop orders.
Not true for a generic theory!

The Quality Problem and reinforced Axion potential

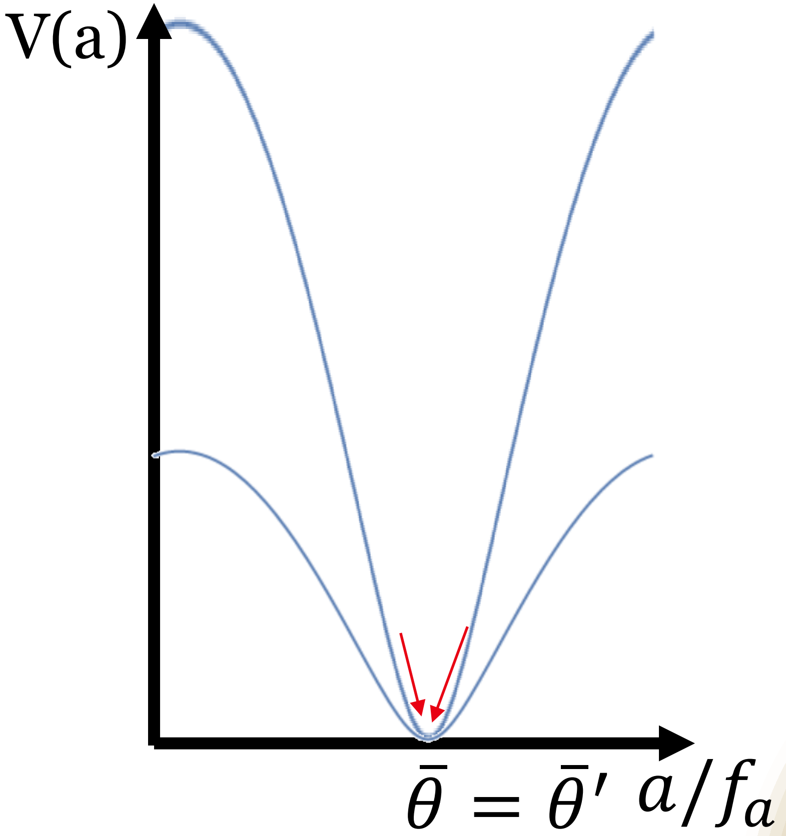
Makes the Quality problem better

$$V \approx -(100\,\mathrm{MeV})^4 \cos\left(\bar\theta - \frac{a}{f_a}\right) - (10^8\,\mathrm{MeV})^4 \cos\left(\bar\theta - \frac{a}{f_a}\right)$$

$$+\Lambda^4_{\mathrm{contamination}} \cos\left(\theta' - \frac{a}{f_a}\right)$$

$$\Lambda_{\mathrm{contamination}} < 10^5\,\mathrm{MeV}$$

Reinforced Axion Potential



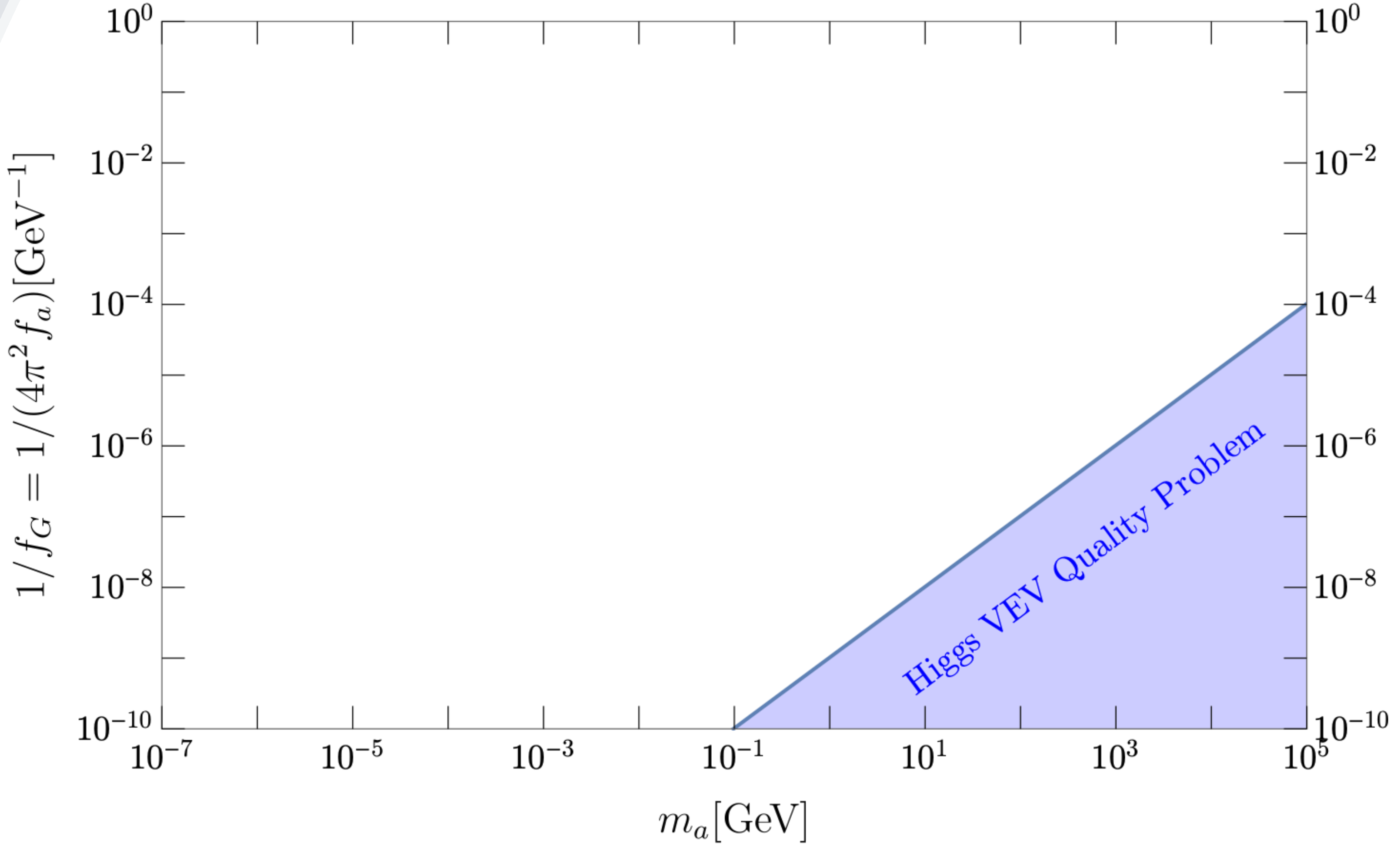
But generates a new quality problem:

$$\frac{g^2}{32\pi^2}\left(\frac{HH^\dagger}{M_{pl}^2} G\tilde G + \frac{H'H'^\dagger}{M_{pl}^2} G'\tilde G'\right)$$

$$H' \lesssim 10^{14}\,\mathrm{GeV}$$

Theory parameter space

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



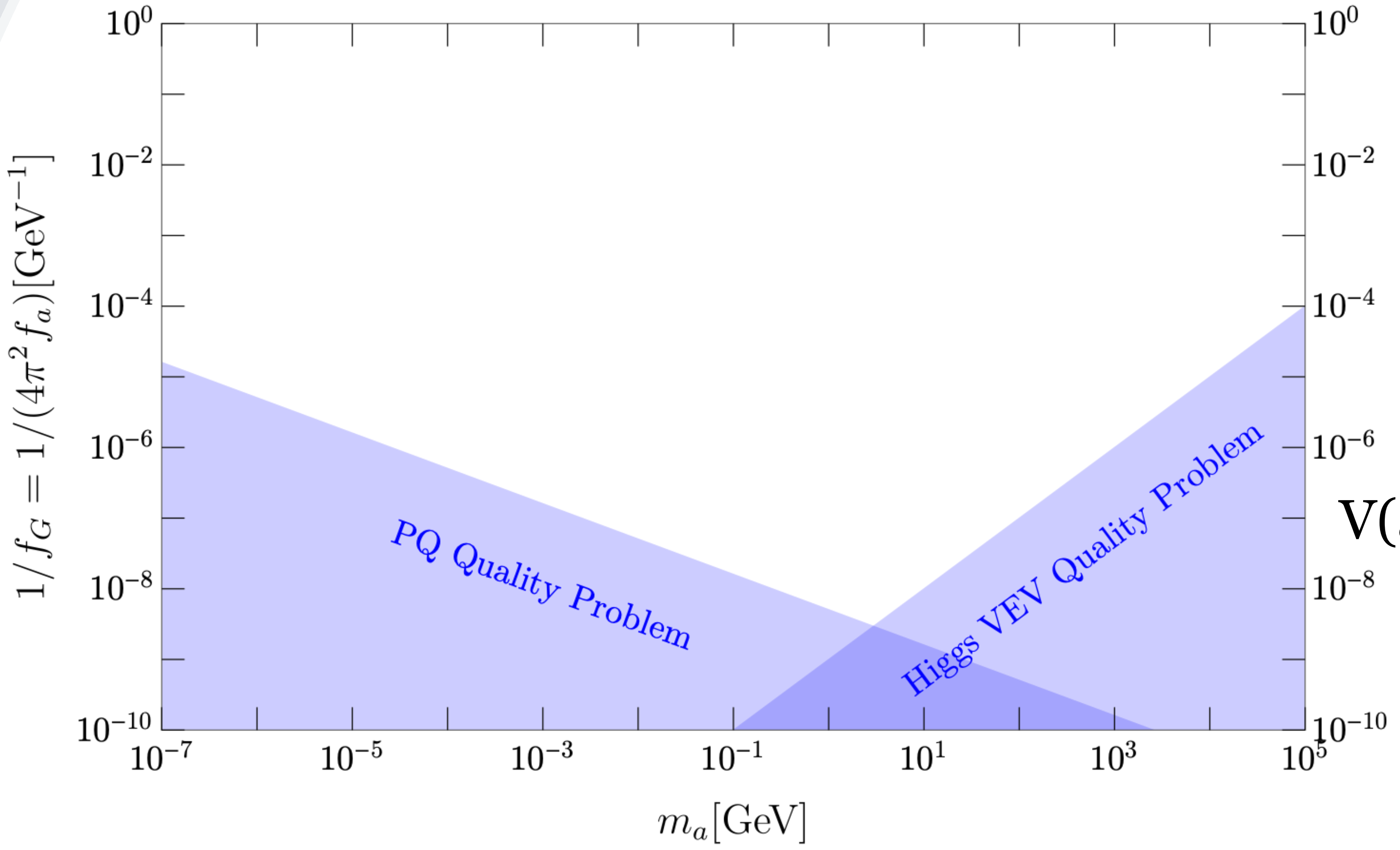
$$\frac{\alpha_3}{8\pi}\left(\frac{H^\dagger H}{M_p^2} G\tilde{G} + \frac{H'^\dagger H'}{M_p^2} G'\tilde{G}'\right)$$

$$\Rightarrow \langle H' \rangle = \mu' < 10^{14}\text{GeV}$$

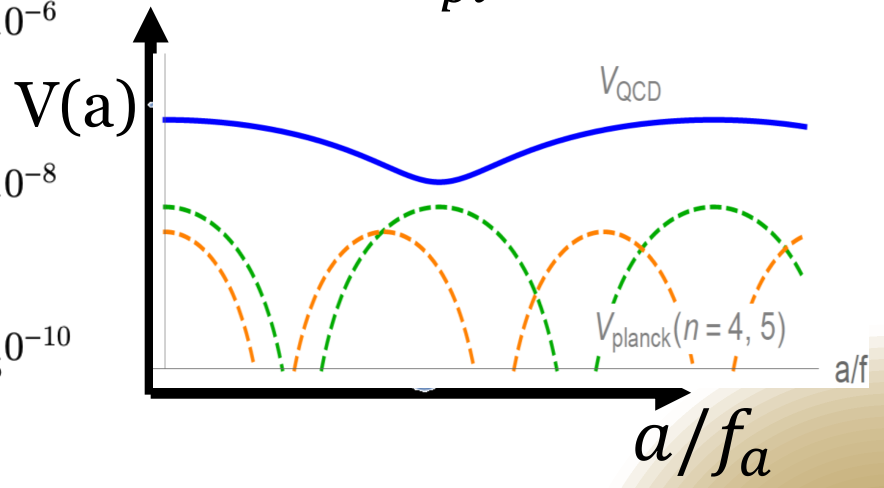
$$\frac{a}{8\pi f_a}\left(c_3\alpha_3 G\tilde{G} + c_2\alpha_2 W\tilde{W} + c_1\alpha_1 B\tilde{B}\right)$$

Theory parameter space

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



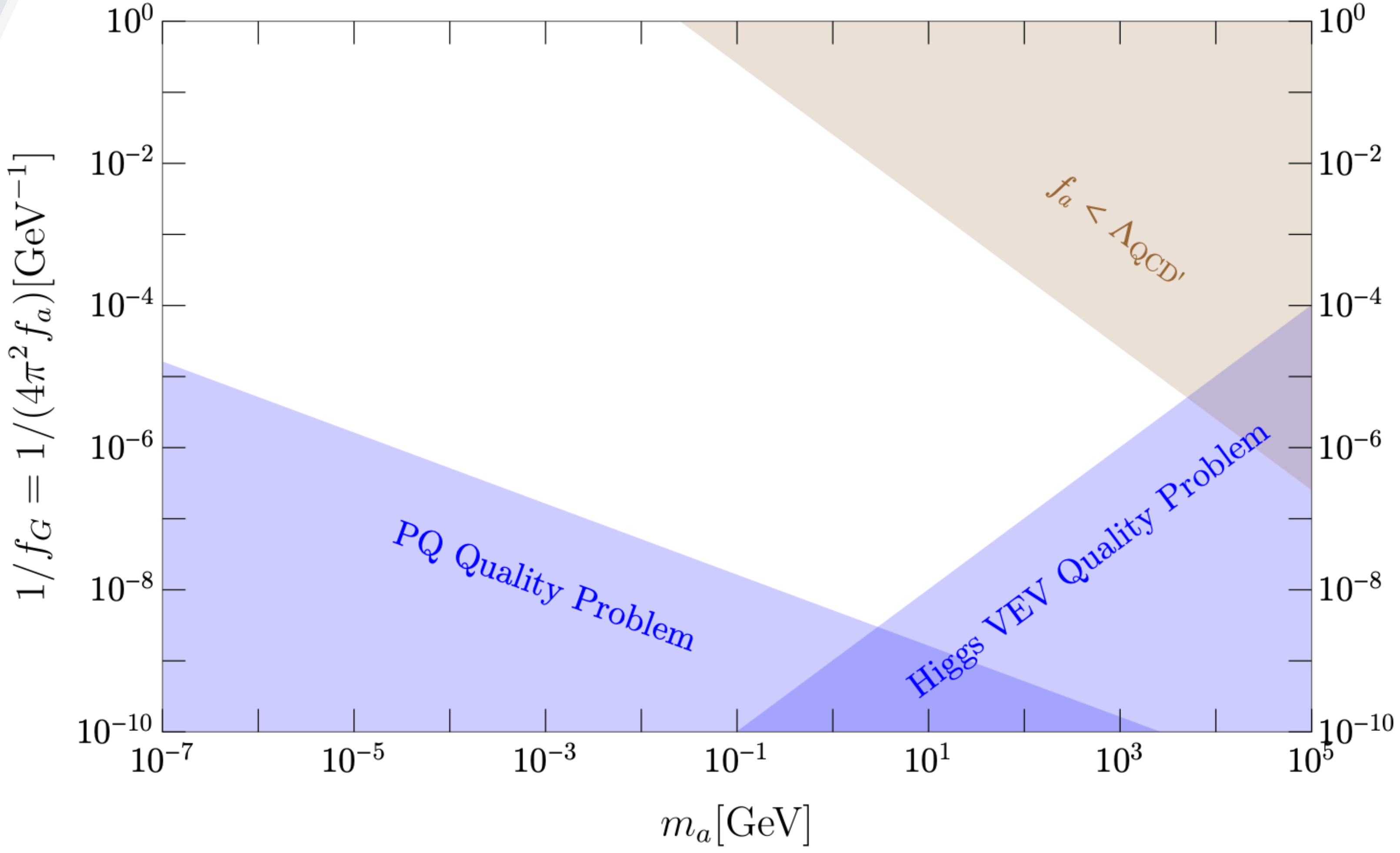
$$\frac{\Phi^6}{M_{pl}^2}$$



$$\frac{a}{8\pi f_a}\left(c_3\alpha_3 G\tilde{G} + c_2\alpha_2 W\tilde{W} + c_1\alpha_1 B\tilde{B}\right)$$

Theory parameter space

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



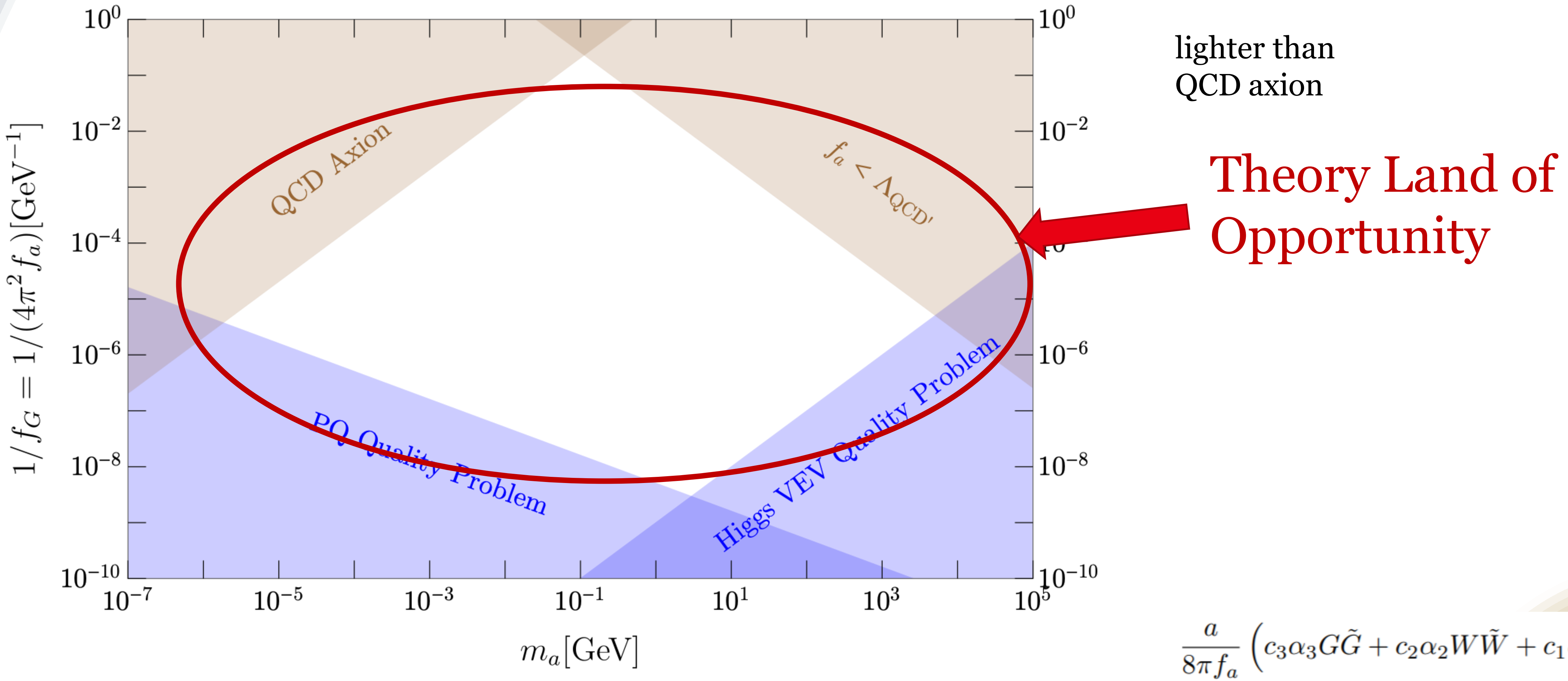
no axion EFT control

$$m_a > f_a$$

$$\frac{a}{8\pi f_a}\left(c_3\alpha_3 G\tilde{G} + c_2\alpha_2 W\tilde{W} + c_1\alpha_1 B\tilde{B}\right)$$

Theory parameter space

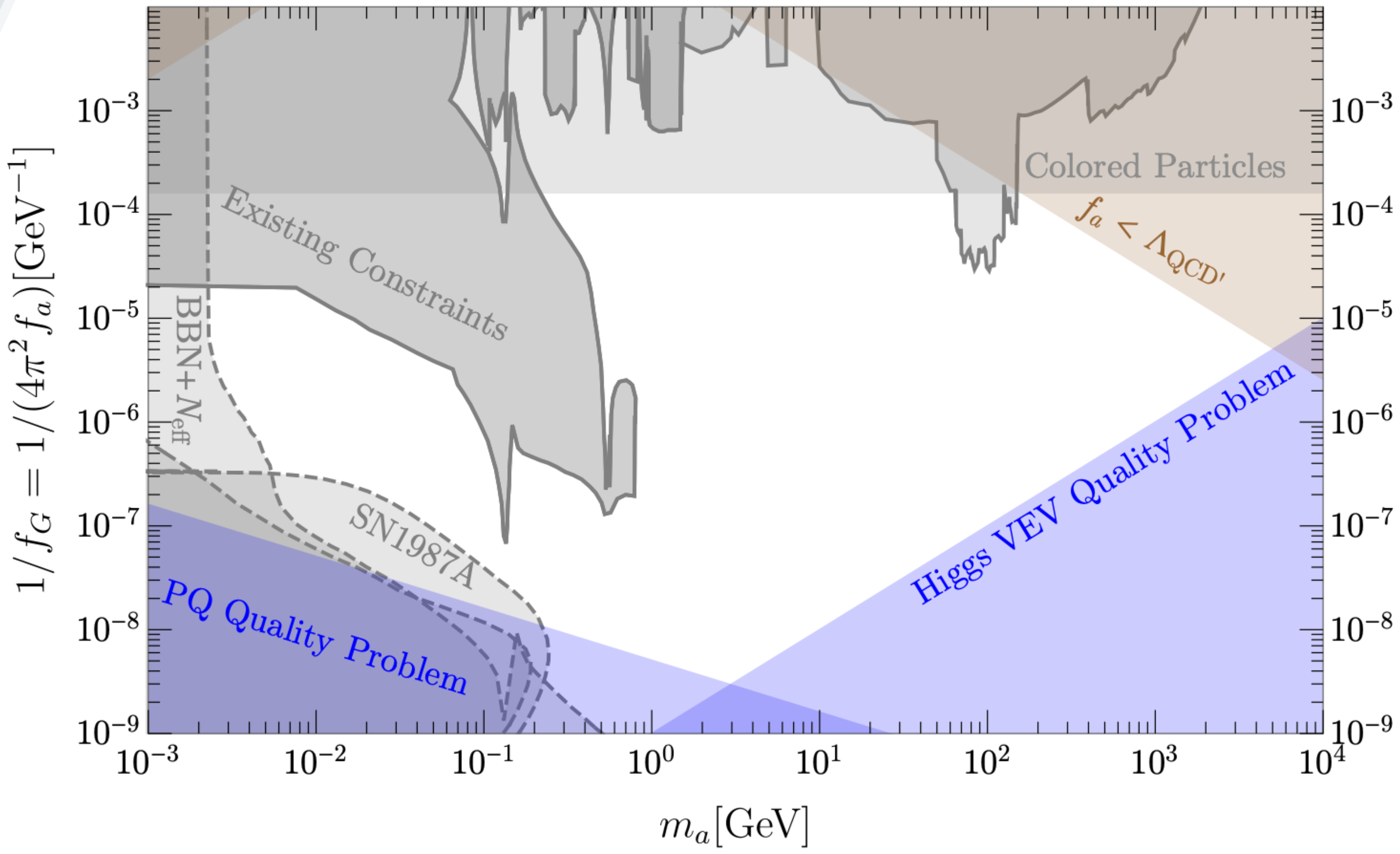
$$m_a^2 \simeq \frac{\Lambda_{QCD'}^4}{f_a^2}$$



lighter than QCD axion

$$\frac{a}{8\pi f_a}\left(c_3\alpha_3 G\tilde{G} + c_2\alpha_2 W\tilde{W} + c_1\alpha_1 B\tilde{B}\right)$$

Existing constraints

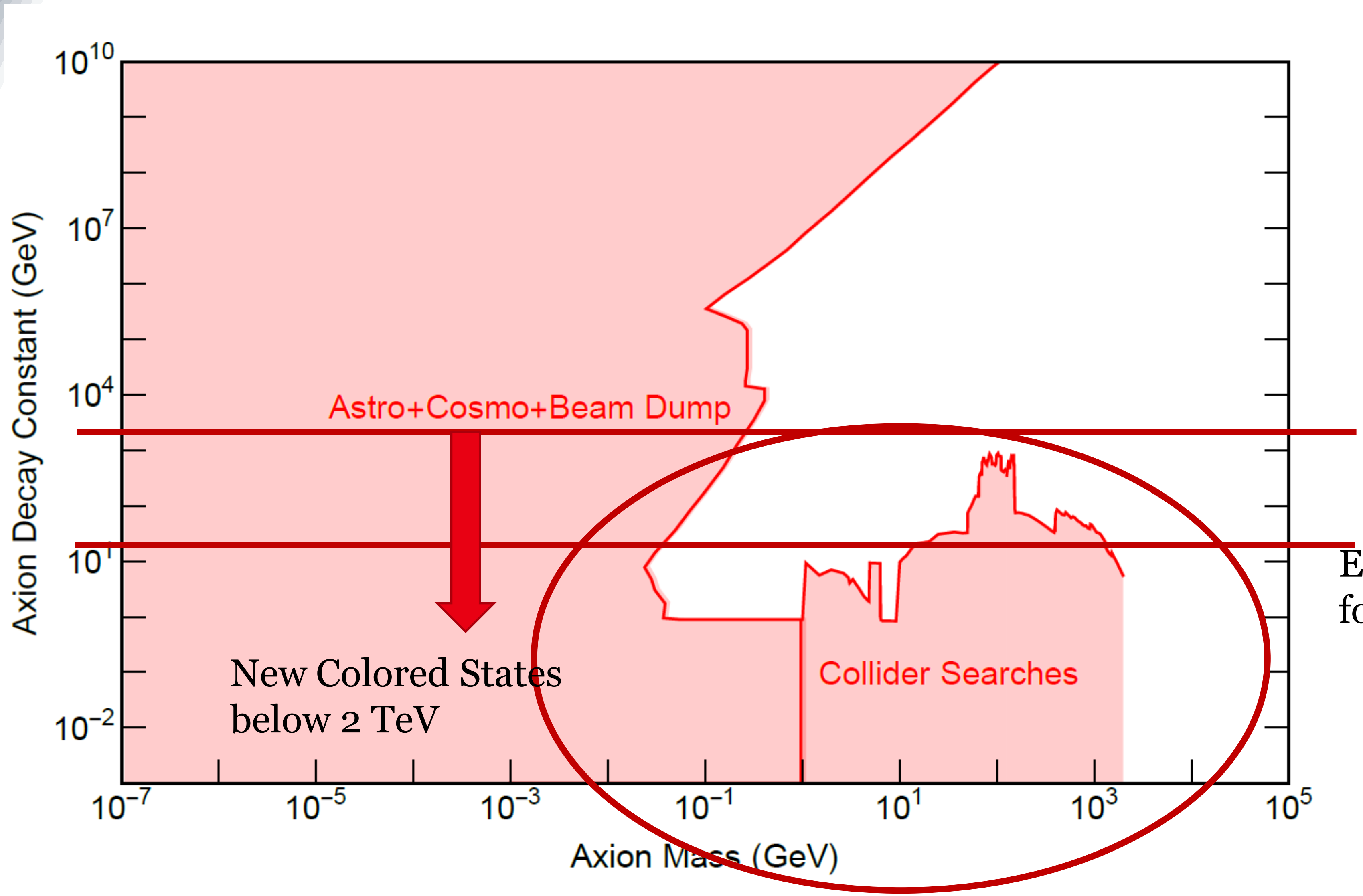


$$\frac{a}{8\pi f_a}\left(c_3\alpha_3 G\tilde{G} + c_2\alpha_2 W\tilde{W} + c_1\alpha_1 B\tilde{B}\right)$$

$$c_1 = c_2 = c_3 = 1$$

$$\frac{a}{8\pi f_a}\left(c_3\alpha_3 G\tilde{G} + c_2\alpha_2 W\tilde{W} + c_1\alpha_1 B\tilde{B}\right)$$

Preferred parameter space



EFT invalid regime
for Collider Pheno*

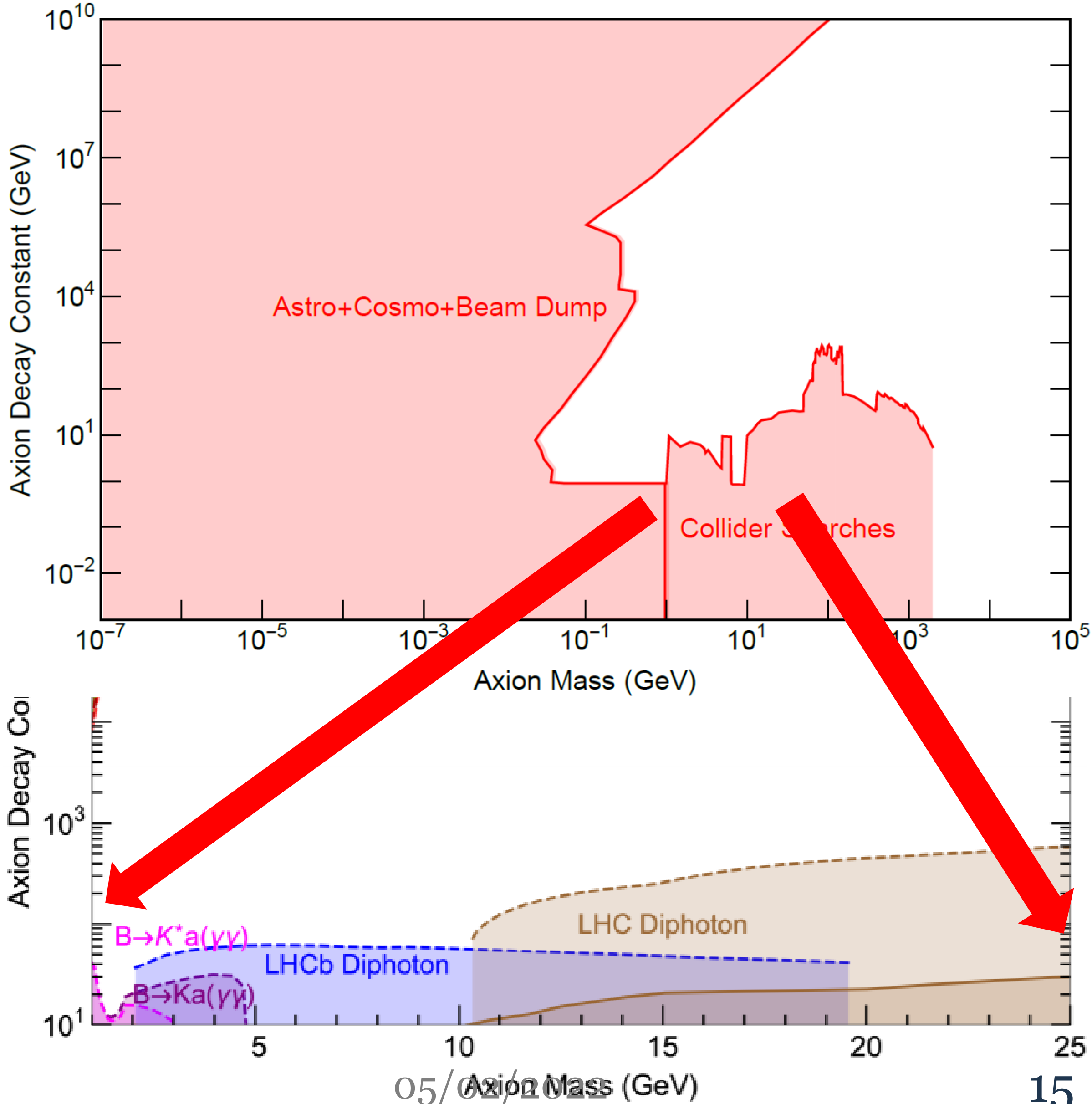
$$\frac{a}{8\pi f_a}\left(c_3\alpha_3 G\tilde{G} + c_2\alpha_2 W\tilde{W} + c_1\alpha_1 B\tilde{B}\right)$$

Preferred parameter space

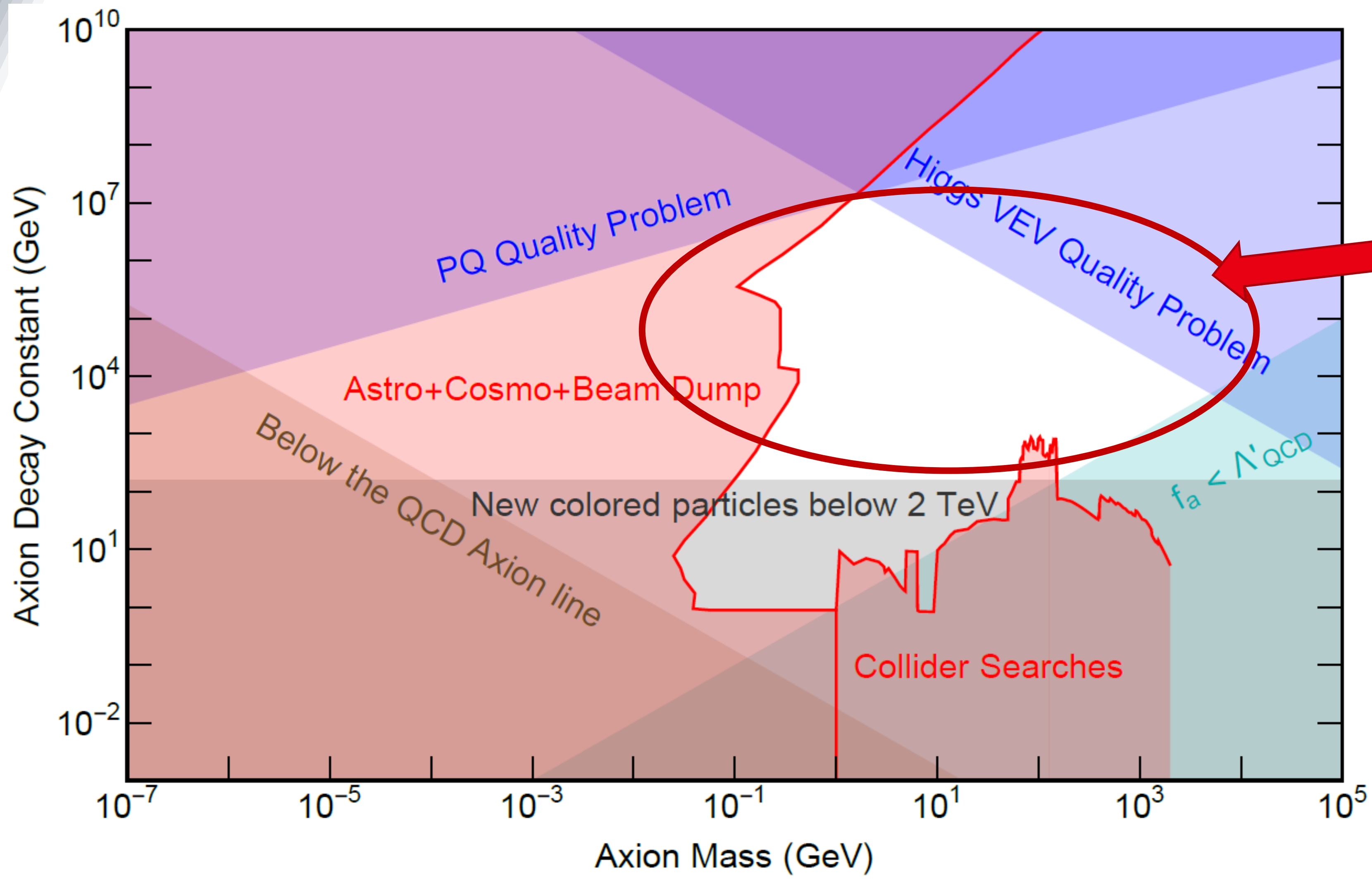
$\tilde{G}G$ the defining coupling for strong CP
Constraints and studies in the GeV scale realm very minimal.
The existing studies focus on photonic, Higgs decays and leptonic couplings.

Hadronic mode buried under QCD background

$$\frac{\alpha_s}{8\pi}\left(\theta + \frac{a}{f_a}\right)\tilde{G}G + \frac{\alpha}{8\pi}\frac{\boldsymbol{a}}{f_a^{\gamma\gamma}}\boldsymbol{\tilde{F}F}$$

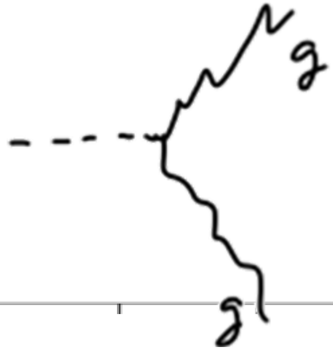


Preferred parameter space

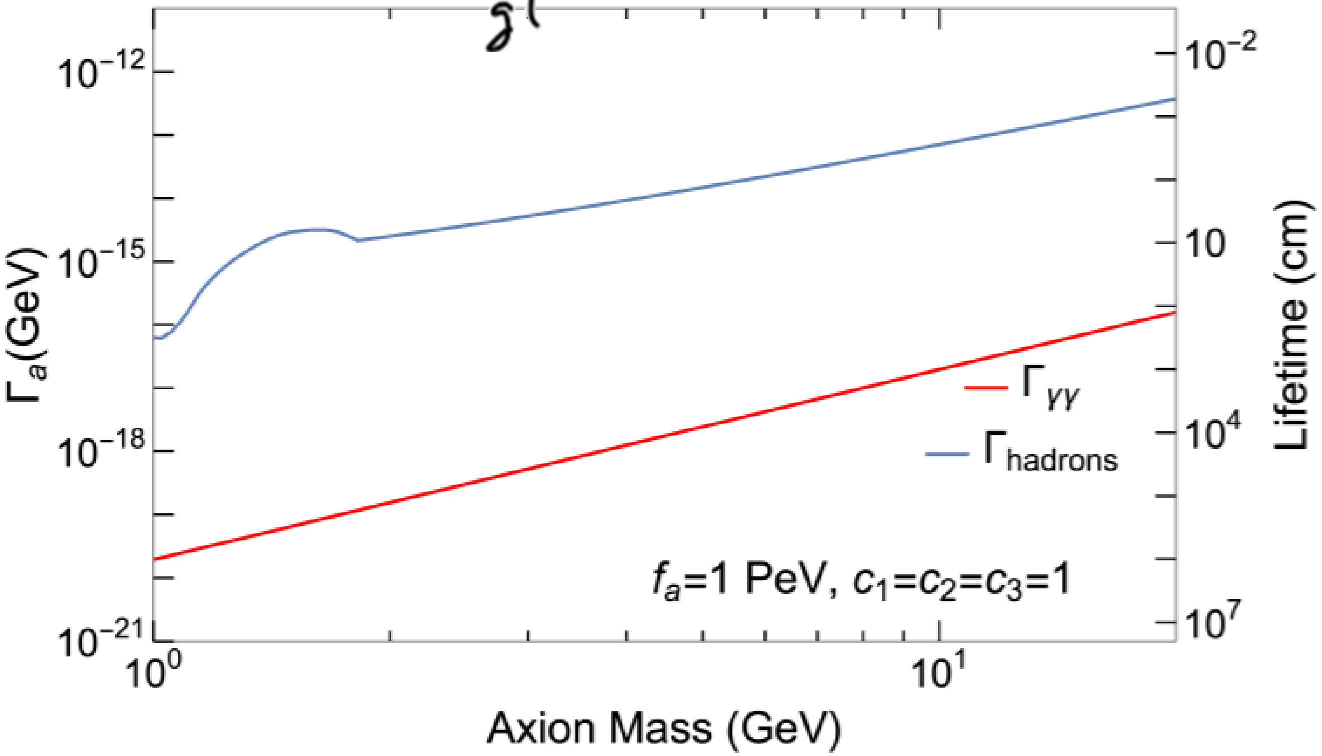


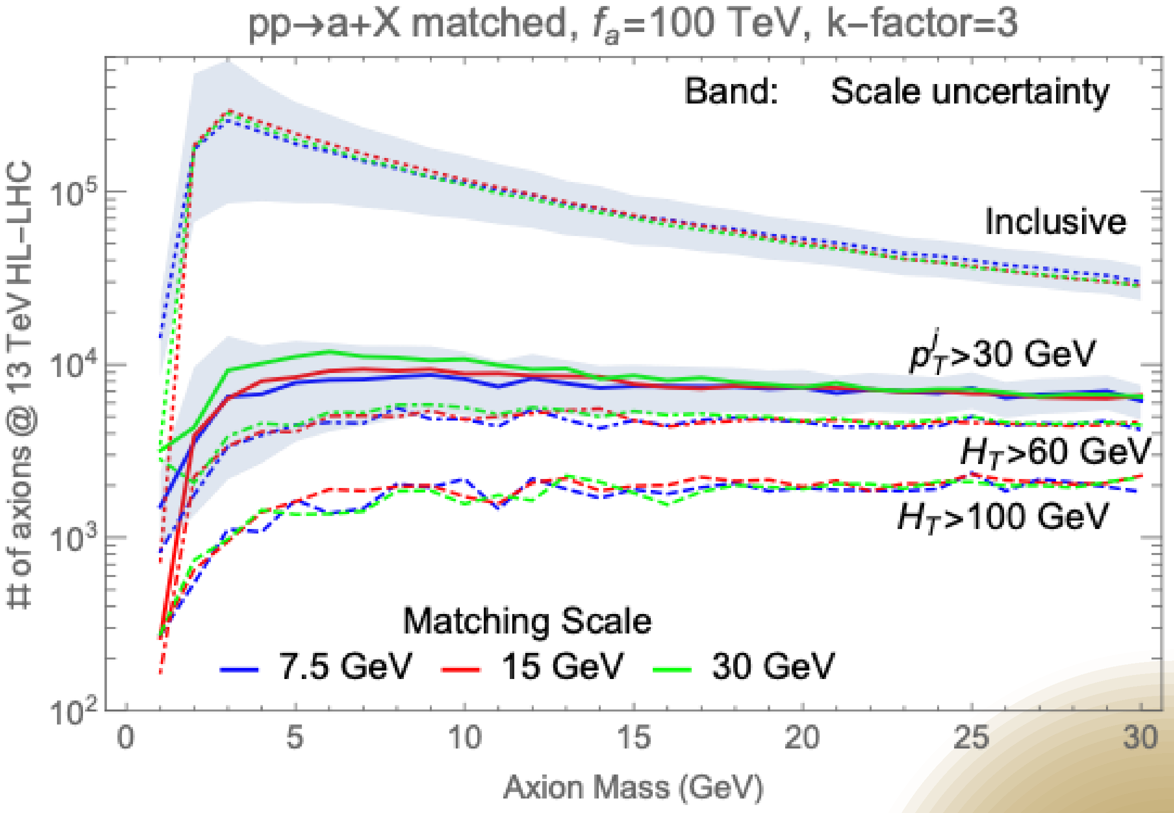
Land of Opportunity (and challenge)

Long-lived Axion



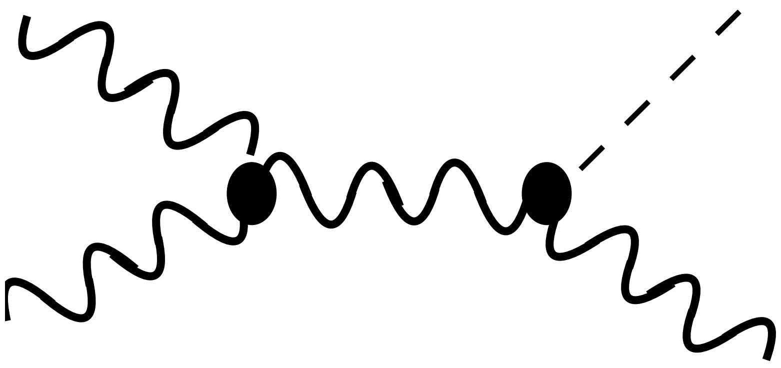
$$\frac{\alpha_s}{8\pi}\left(\theta+\frac{a}{f_a}\right)\tilde{G}G+\frac{\alpha}{8\pi}\frac{\boldsymbol{a}}{f_a^{\gamma\gamma}}\widetilde{\boldsymbol{F}}\boldsymbol{F}$$





Displaced track trigger: crucial ingredient

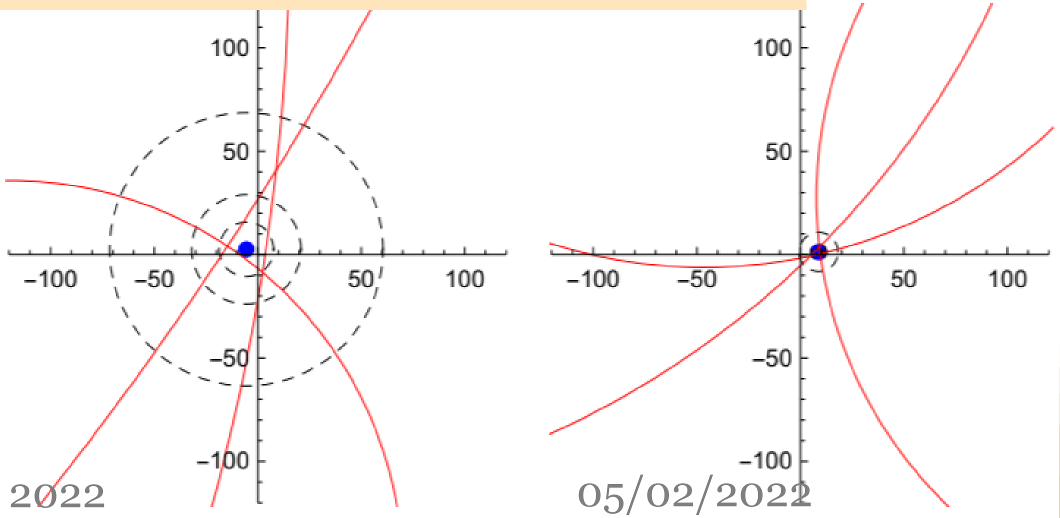
- At least three $p_T > 2$ GeV tracks within an L1 jet;
- Amongst the above tracks, at least three of them have the transverse impact parameter $d_0 > 1$ mm;
- The pseudo-rapidity of the tracks to be $|\eta| < 2.4$;
- The event has $H_T > 100$ GeV.



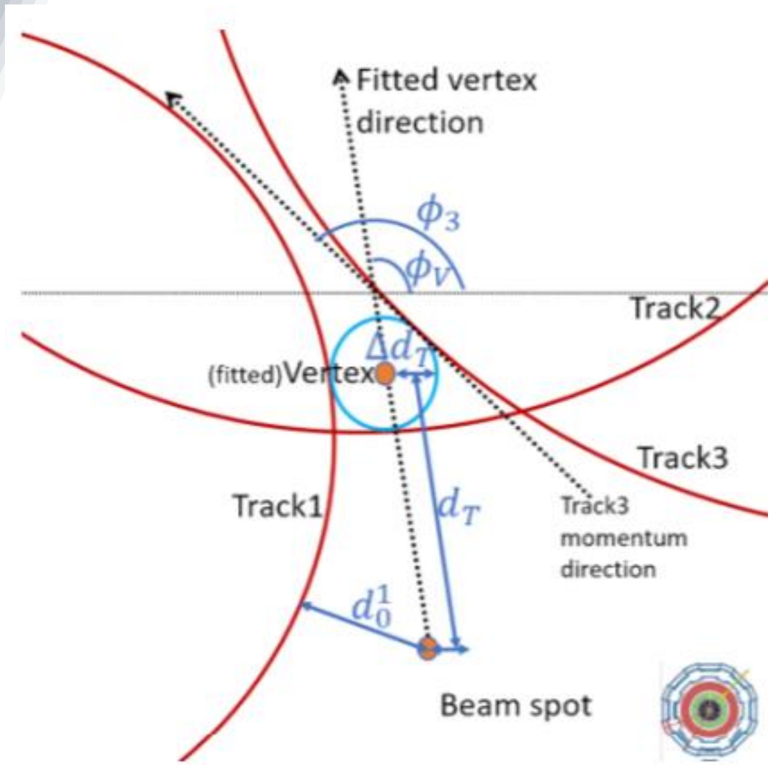
Long-lived signals are produced and decayed through a same vertex

Post L1-triggering Background: 10^{12} (at HL-LHC)

Empirical modeling fake background:
- track impact parameter (|d0| < 15 cm)
- track curvature (1/R ∝ q/pT < 1/(1.8 m))
- track eta |η| < 2.4
- track time t0 (|t0| < 6 ns)
- track z- coordinate (|z0| < 15 cm)

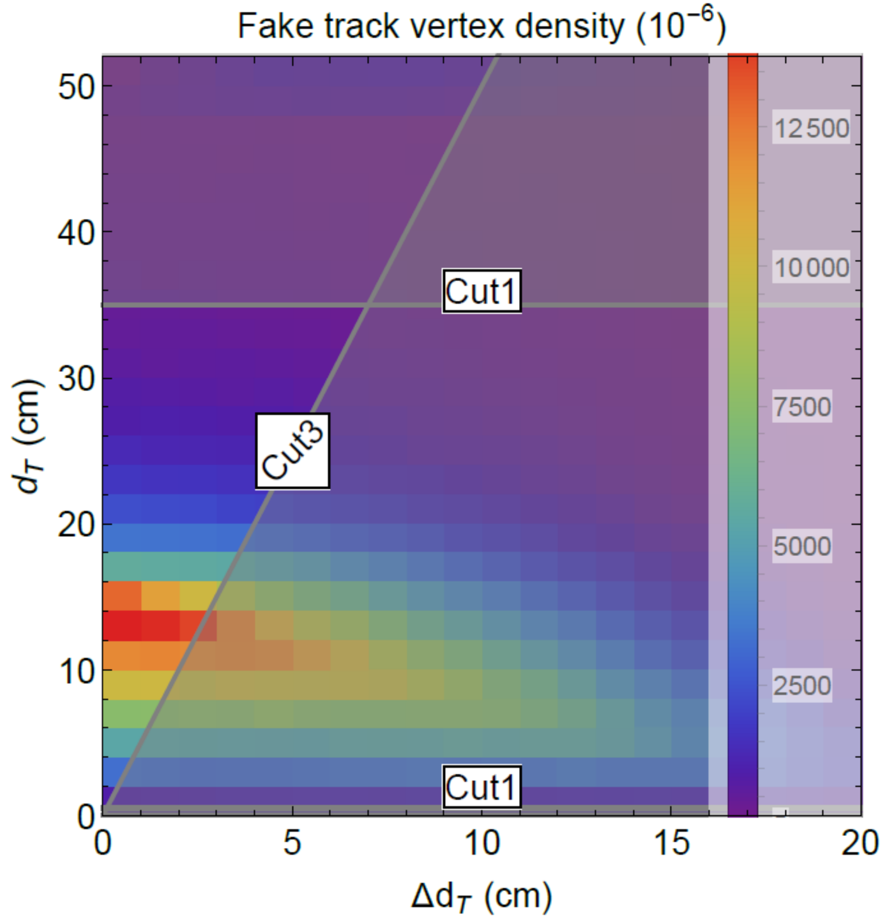


Analysis: 2D-4D vertexing selection

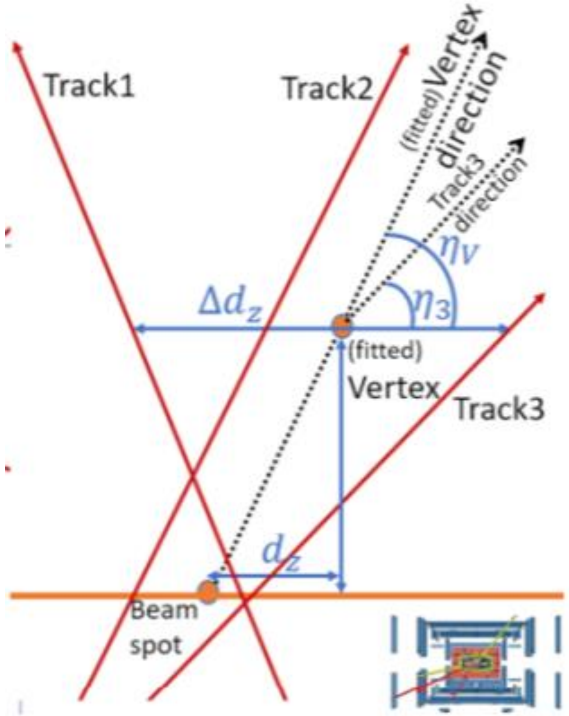


Vertex fitting in the transverse plane. Such consistency requirement provides 8.2×10^{-2} suppression.

1. The 2D common vertex has a minimal distance to the interaction point of 0.5 cm and maximal distance of 35 cm, 0.5 cm $< d_T <$ 35 cm;
2. The 2D tracks fit a common vertex with standard deviation $\Delta d_T < 1$ cm;
3. The 2D common vertex is sufficiently displaced away from the interaction point, $d_T/\Delta d_T > 5$;



Analysis: 2D-4D vertexing selection

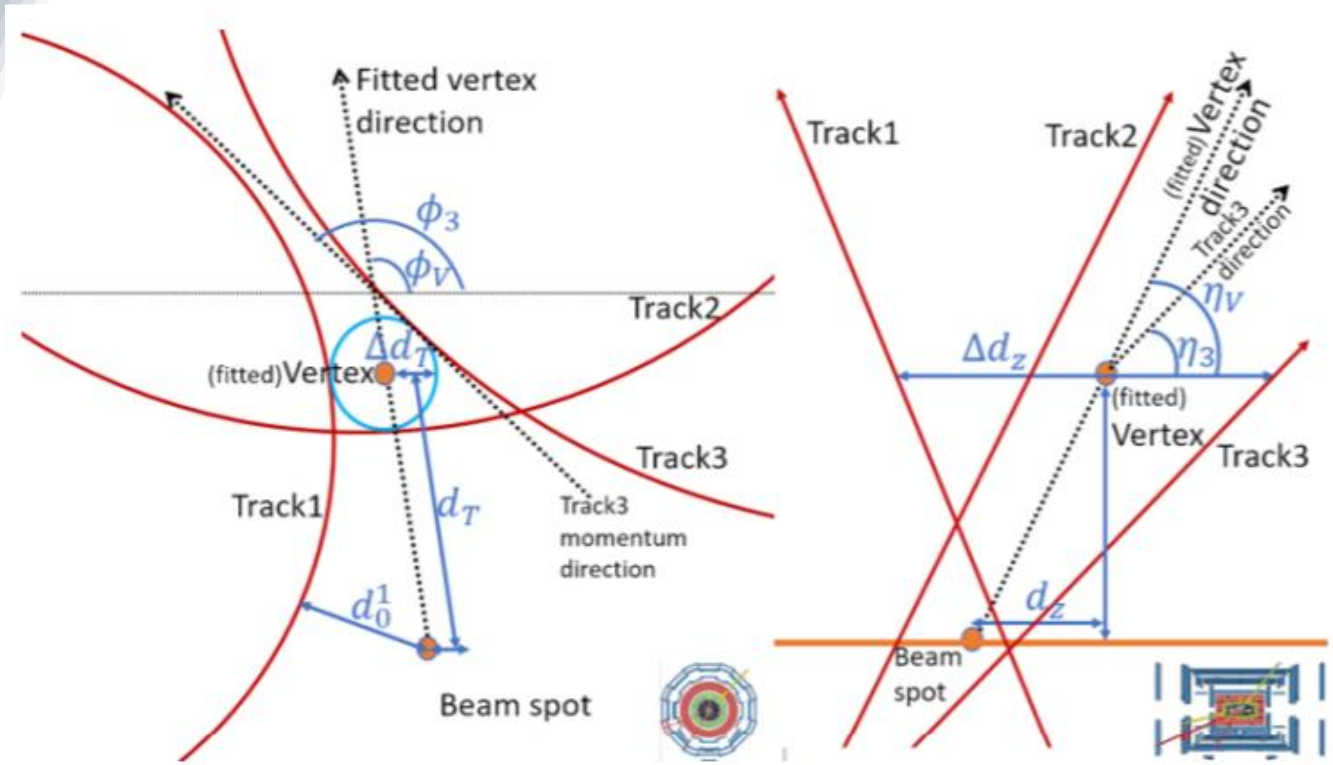


4. The corresponding 4D vertex has a standard deviation in z direction $\Delta d_z < 5$ cm;
5. The corresponding 4D vertex has a z-direction location $d_z < 20$ cm;
6. The corresponding 4D vertex has a standard deviation in time $\Delta d_t < 500$ ps;
7. The corresponding 4D vertex has a time $d_t < 1000$ ps;

Derived from the 2D fit results, one further imposes the consistency requirements between the three track in the z-direction and t-direction, providing 4.9×10^{-2} and 3.0×10^{-3} suppression, respectively.

Hook, Kumar, ZL, Sundrum, 1911.12364

Analysis: 2D-4D vertexing selection



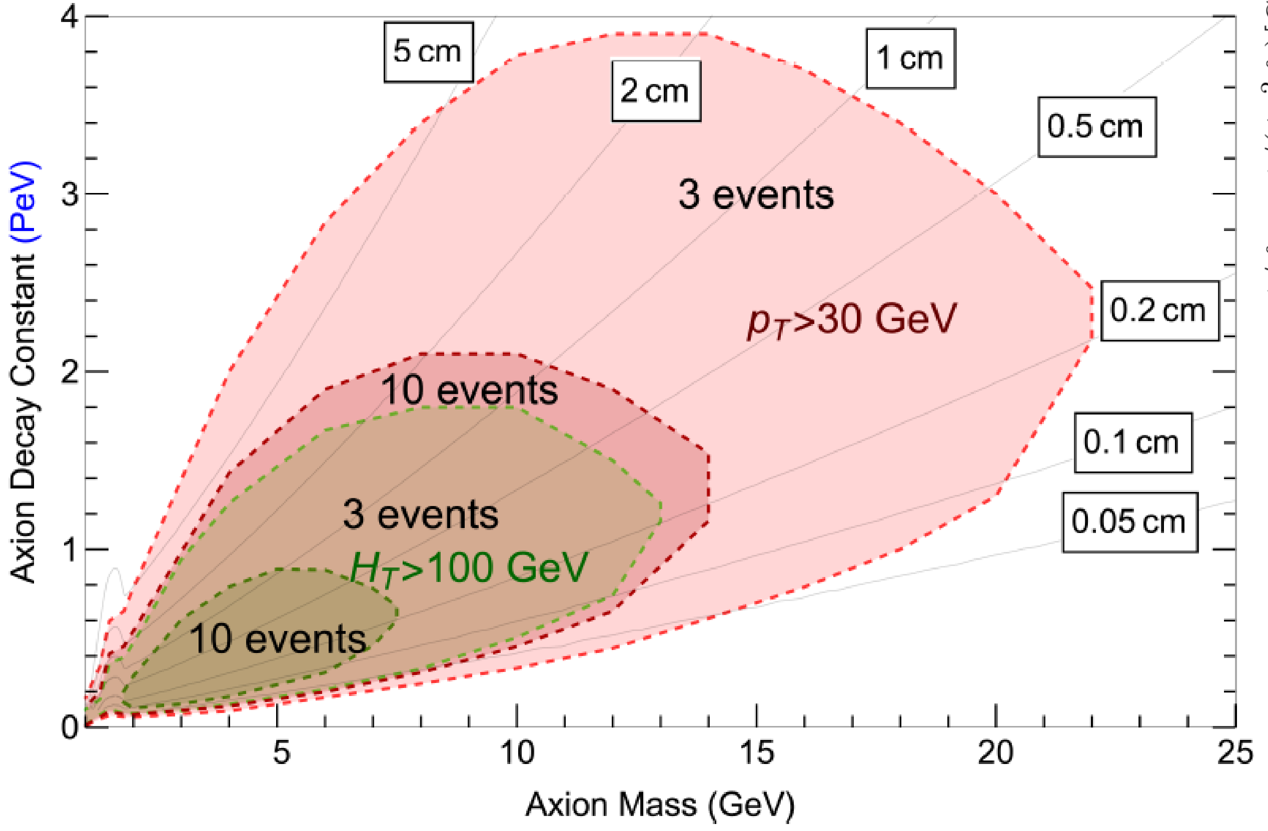
Background: 10^12 to begin with (post triggering);
2D-4D vertexing reduces it to 10^3
Track/jet information matching between different subdetectors can further reduce it to <1

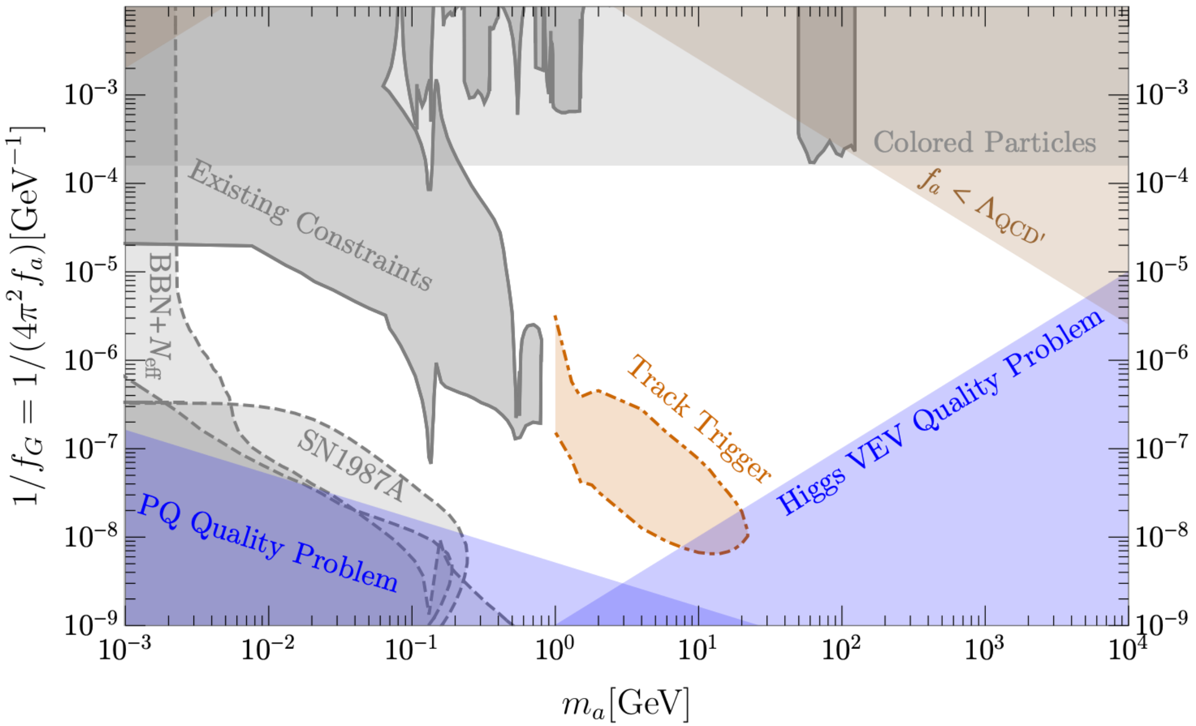
1. The 2D common vertex has a minimal distance to the interaction point of 0.5 cm and maximal distance of 35 cm, 0.5 cm $< d_T <$ 35 cm;
2. The 2D tracks fit a common vertex with standard deviation $\Delta d_T < 1$ cm;
3. The 2D common vertex is sufficiently displaced away from the interaction point, $d_T/\Delta d_T > 5$;
4. The corresponding 4D vertex has a standard deviation in z direction $\Delta d_z < 5$ cm;
5. The corresponding 4D vertex has a z-direction location $d_z < 20$ cm;
6. The corresponding 4D vertex has a standard deviation in time $\Delta d_t < 500$ ps;
7. The corresponding 4D vertex has a time $d_t <$ 1000 ps;
8. The tracks are within 0.4 in pseudorapidity of the reconstructed displaced jet direction $|\eta_i - \eta_V| < 0.4$ for all the three tracks;
9. The tracks are within 0.4 in azimuthal angle of the reconstructed displaced jet direction $|\phi_i - \phi_V| < 0.4$ for all the three tracks;

A displaced track trigger enables searches for axions

Unique singly produced LLPs making the LHC main detectors the major place to look for them:

Long lifetime = low production rate



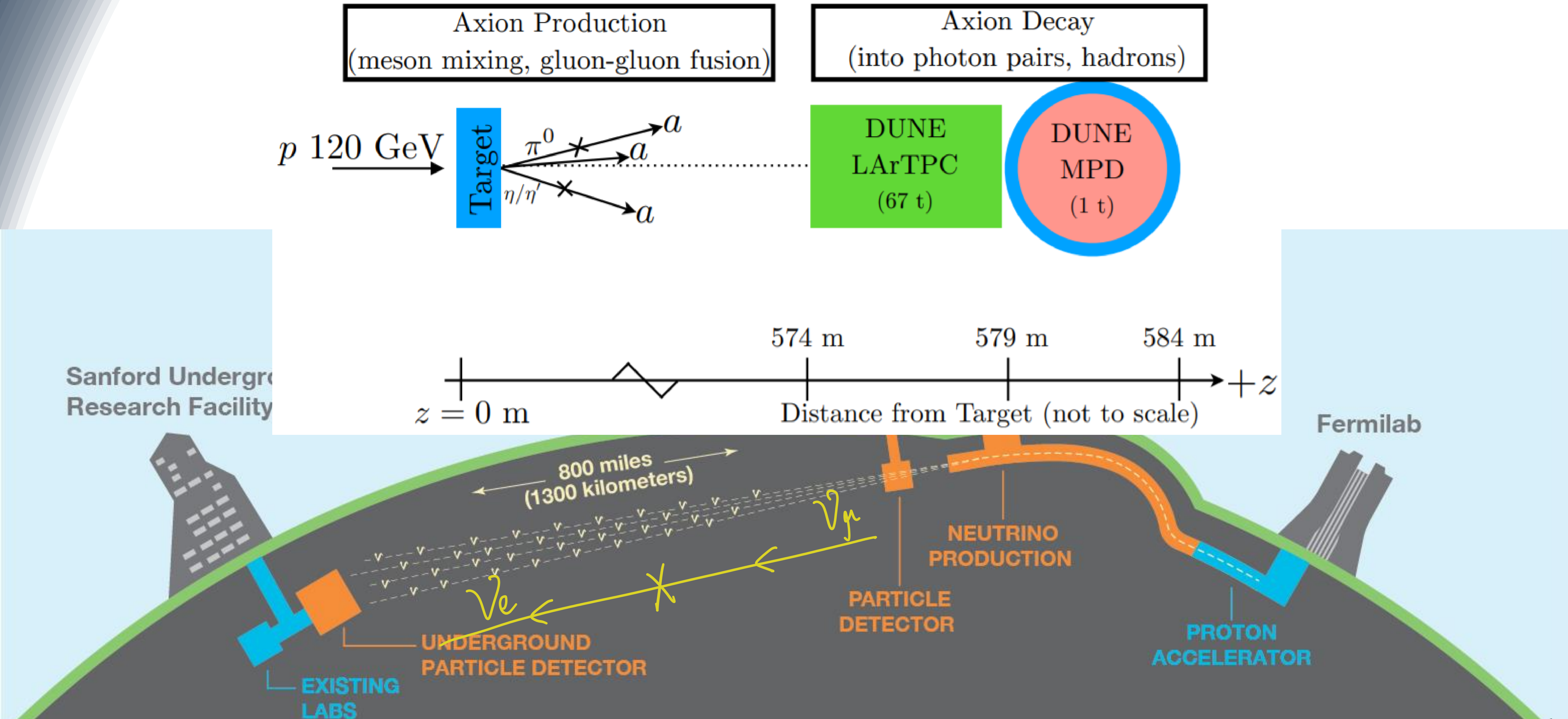


We employ a 2D-4D vertexing selection for displaced jet to veto the fake track background, demonstrating the plausibility of this search.

See also nice discussion on "dark pion" pheno in Cheng, Li, Salvioni, 2110.10691

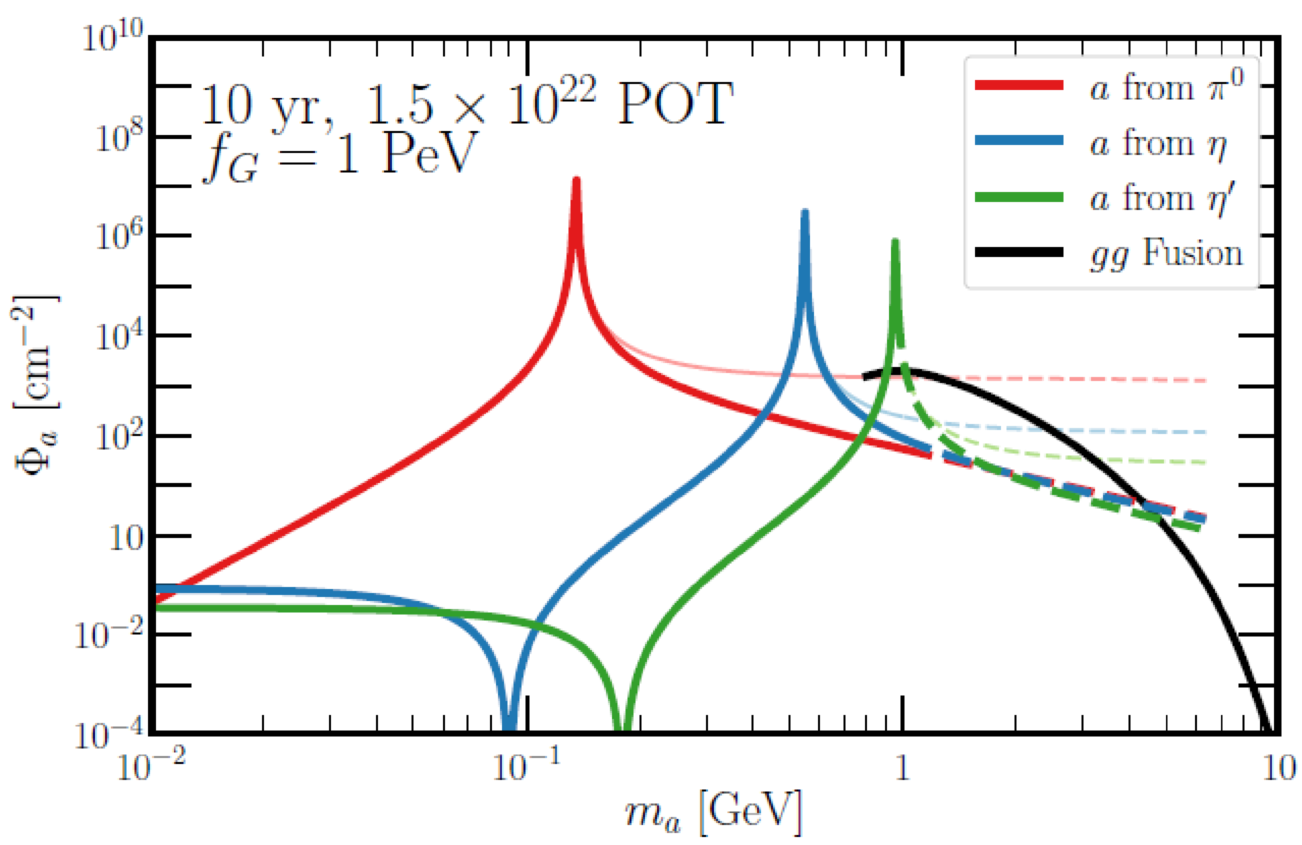
It is GeV, not TeV scale new physics. Can we do better?

DUNE: excellent for heavy Axions



Kelly, Kumar, ZL, 2011.05995

DUNE setup



large flux

1.47×10^{21} POT/yr.

$$\pi = \pi_{\rm phys} + \theta_{a\pi} a_{\rm phys} + \cdots \approx \pi_{\rm phys} + \frac{1}{6}\frac{f_\pi}{f_a}\frac{m_a^2}{m_a^2 - m_\pi^2} a_{\rm phys} + \cdots,$$

$$\eta = \eta_{\rm phys} + \theta_{a\eta} a_{\rm phys} + \cdots \approx \eta_{\rm phys} + \frac{1}{\sqrt{6}}\frac{f_\pi}{f_a}\left(\frac{m_a^2 - \frac{4}{9}m_\pi^2}{m_a^2 - m_\eta^2}\right) a_{\rm phys} + \cdots,$$

$$\eta' = \eta'_{\rm phys} + \theta_{a\eta'} a_{\rm phys} + \cdots \approx \eta'_{\rm phys} + \frac{1}{2\sqrt{3}}\frac{f_\pi}{f_a}\left(\frac{m_a^2 - \frac{16}{9}m_\pi^2}{m_a^2 - m_{\eta'}^2}\right) a_{\rm phys} + \cdots$$

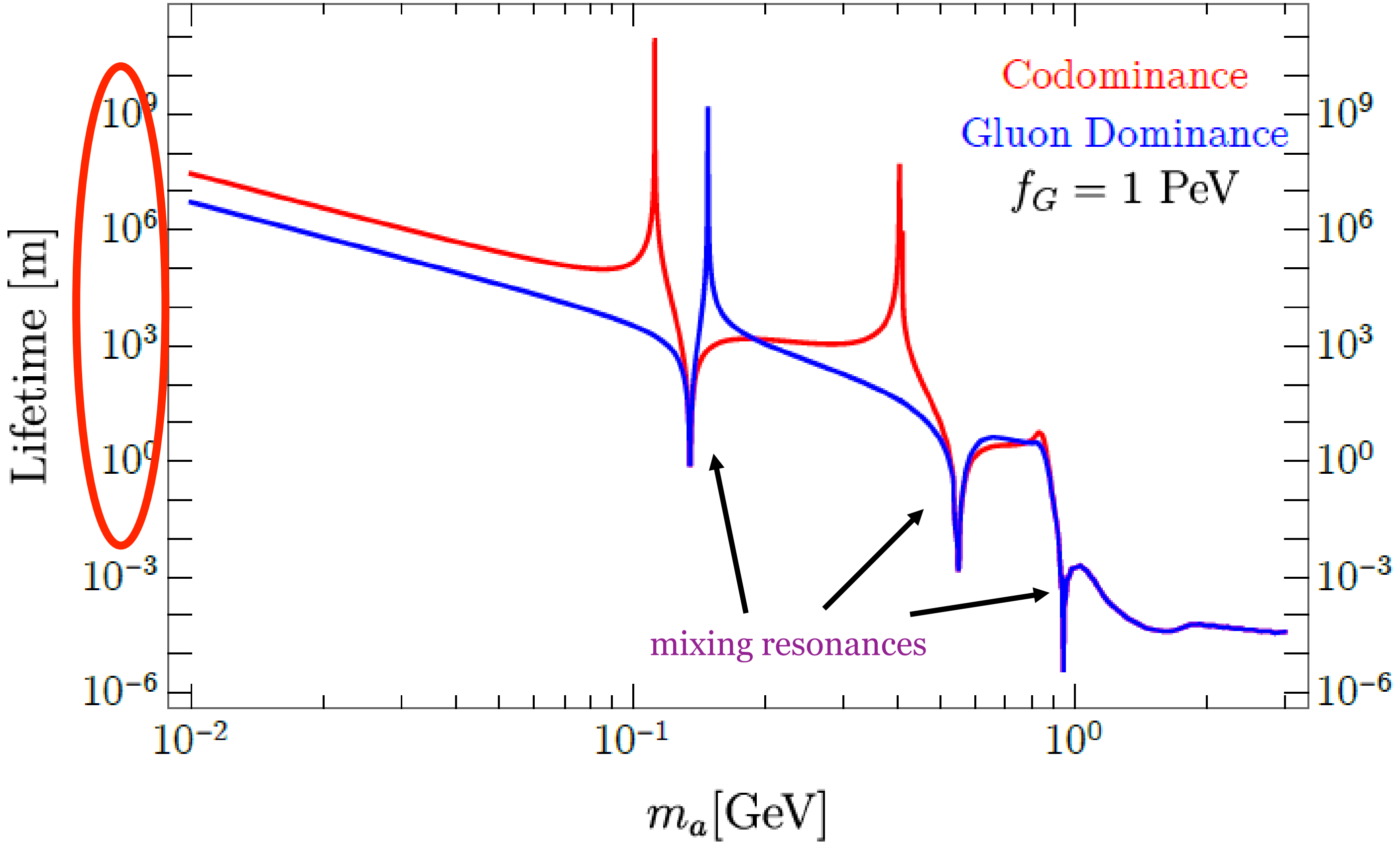
$$N_{\rm axions} = N_{\rm POT} \times \left[2.89|\theta_{a\pi}|^2 f(m_\pi, m_a) + 0.33|\theta_{a\eta}|^2 f(m_\eta, m_a) + 0.03|\theta_{a\eta'}|^2 f(m_{\eta'}, m_a)\right]$$

$$f(m_{\rm meson}, m_a) = \begin{cases} \left(\frac{m_a}{m_{\rm meson}}\right)^{-1.6} & \text{if } m_a > m_{\rm meson} \\ 1 & \text{if } m_a \le m_{\rm meson}. \end{cases}$$

Decay via $\gamma\gamma$ and hadronic states

- DUNE can detect both $\gamma\gamma$ and hadronic final states

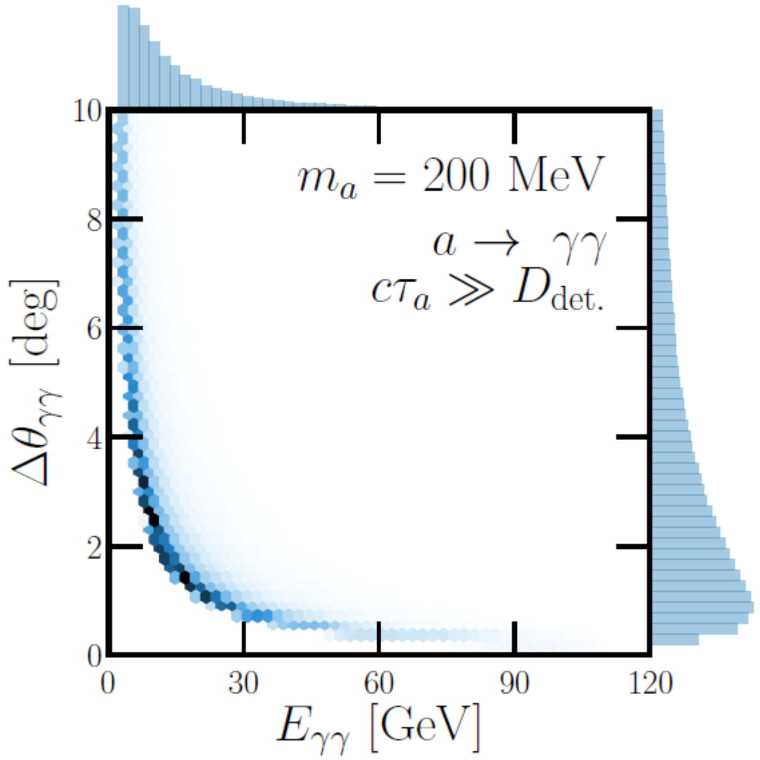
Aloni et. al. '18

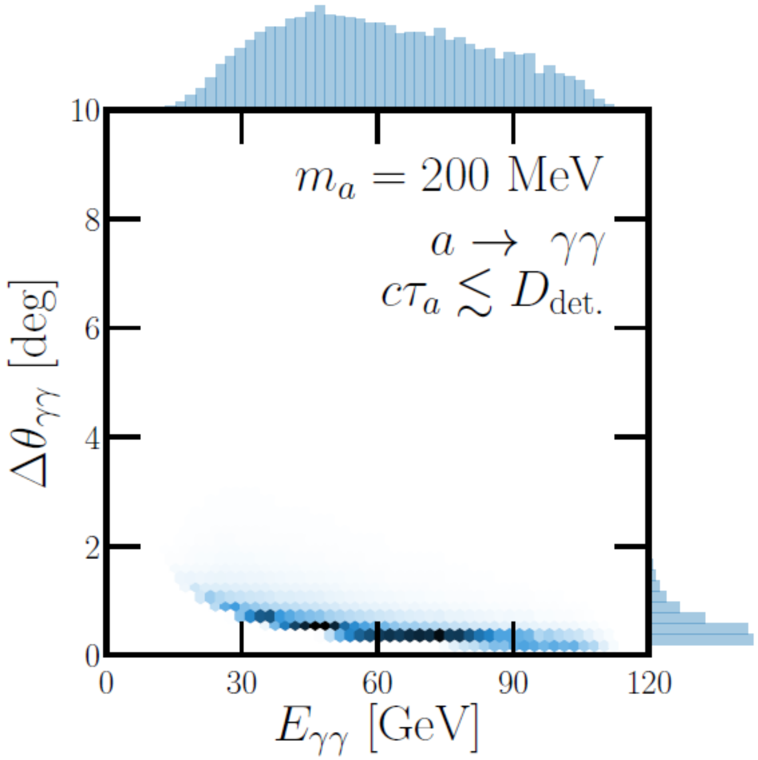


$$c_{\gamma\gamma}^{\text{eff}}(m_a \lesssim \text{GeV})$$
$$\approx c_2 + \frac{5}{3}c_1 - 1.92 c_3$$
$$- c_3 \frac{m_a^2}{m_\pi^2 - m_a^2}\frac{m_d - m_u}{m_d + m_u} + \cdots$$

$$\frac{a}{8\pi f_a}\left(c_3\alpha_3 G\tilde{G} + c_2\alpha_2 W\tilde{W} + c_1\alpha_1 B\tilde{B}\right)$$

Signal and BG considerations for $a \to \gamma\gamma$





Backgrounds from neutral current π are low energy ($\lesssim$ 5GeV) and isotropic

Signature	Liquid Argon ArgonCube		Gaseous Argon MPD	
	Signal	Background	Signal	Background
$a \to \gamma\gamma$	Invariant Mass $\gamma\gamma$ Direction High-Energy	NCπ^0 Nearly-Isotropic Low-Energy	Invariant Mass $\gamma\gamma$ Direction High-Energy	NCπ^0 Nearly-Isotropic Low-Energy Low-energy recoils
$a \to$ hadrons	Invariant Mass Opening angle High-energy gg Direction	CC1μ2π DIS Low-energy Nearly-Isotropic	Invariant Mass Opening angle High-Energy gg Direction	CC1μ2π DIS Low-Energy Nearly-isotropic Low-energy recoils

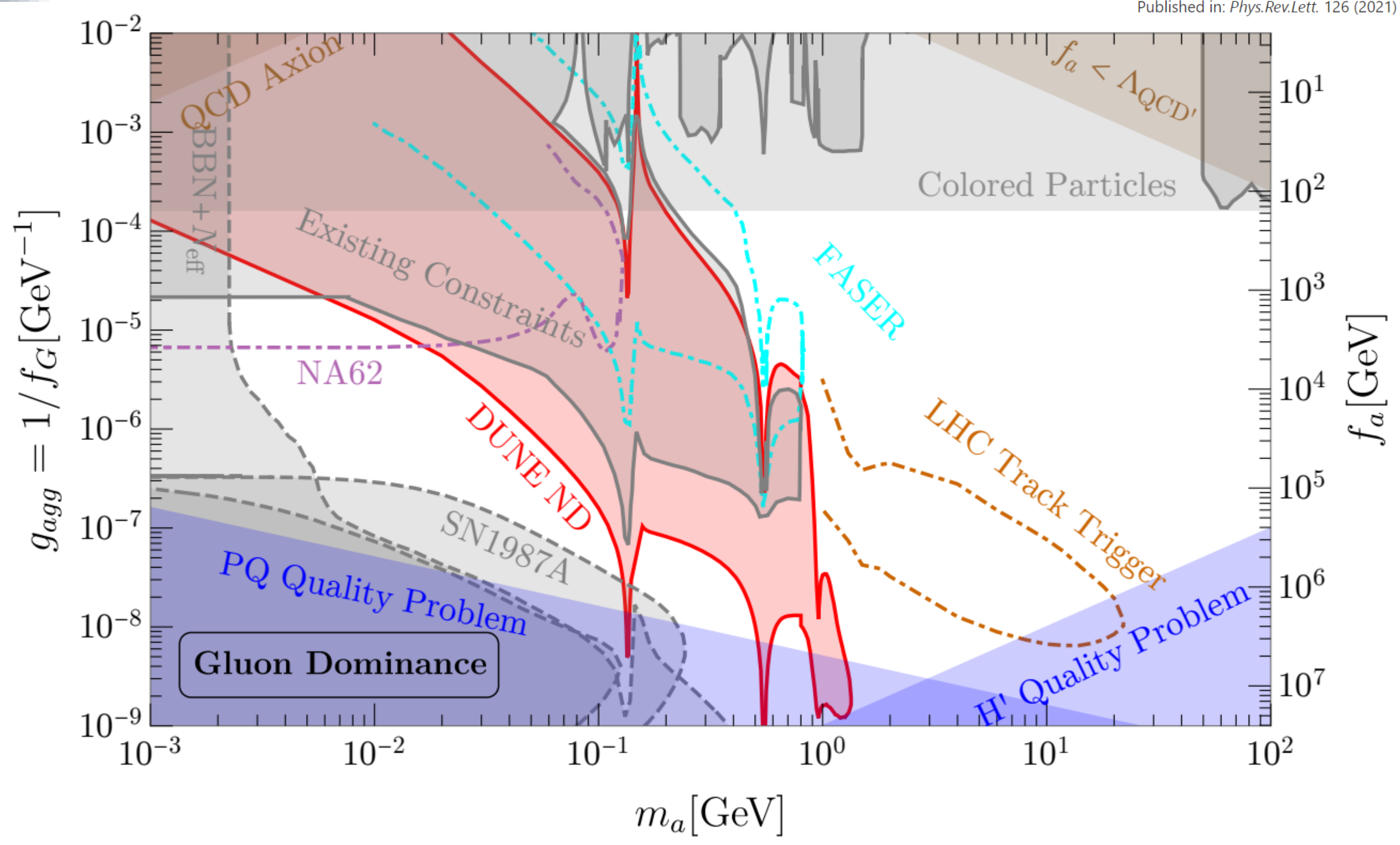
Also see nice work on photon-photon-axion coupling

Axionlike Particles at Future Neutrino Experiments: Closing the Cosmological Triangle

Vedran Brdar (Fermilab and Northwestern U.), Bhaskar Dutta (Texas A-M), Wooyoung Jang (Texas U., Arlington (main)), Doojin Kim (Texas A-M), Ian M. Shoemaker (Virginia Tech., Blacksburg) et al. (Nov 13, 2020)

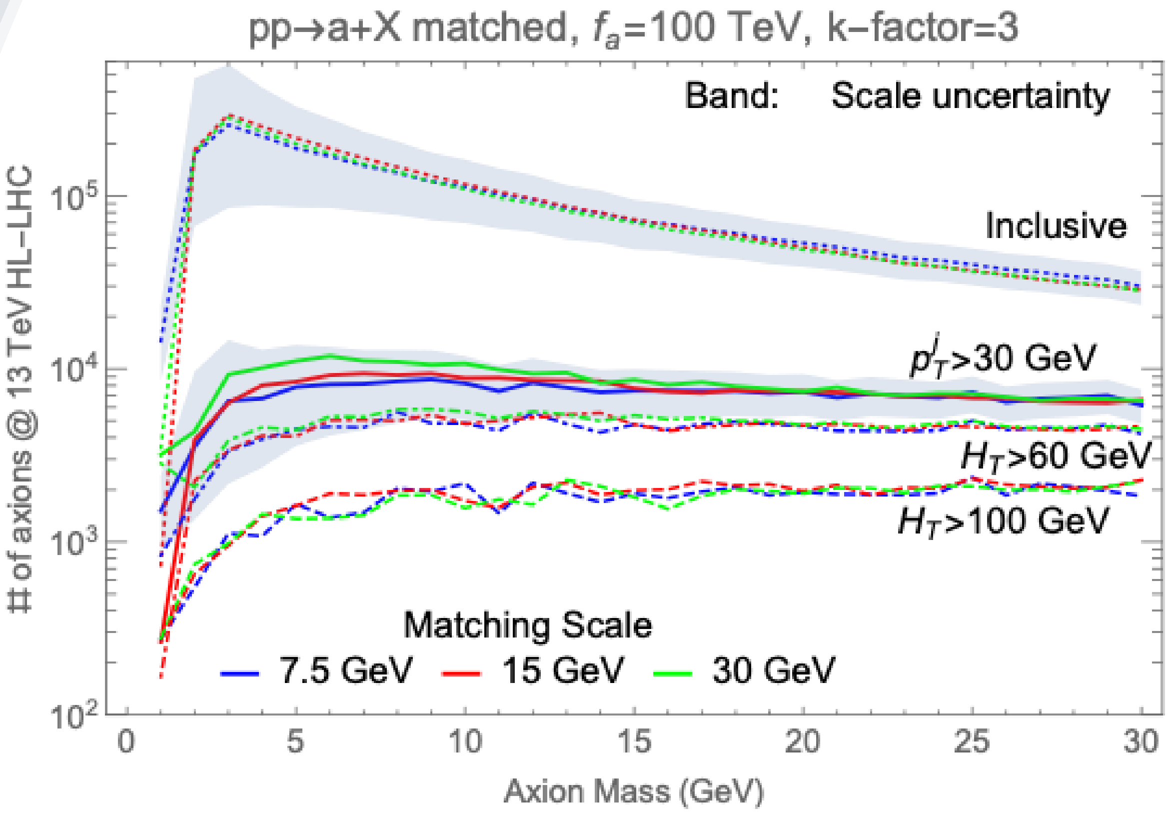
Published in: *Phys.Rev.Lett.* 126 (2021) 20, 201801 • e-Print: 2011.07054 [hep-ph]

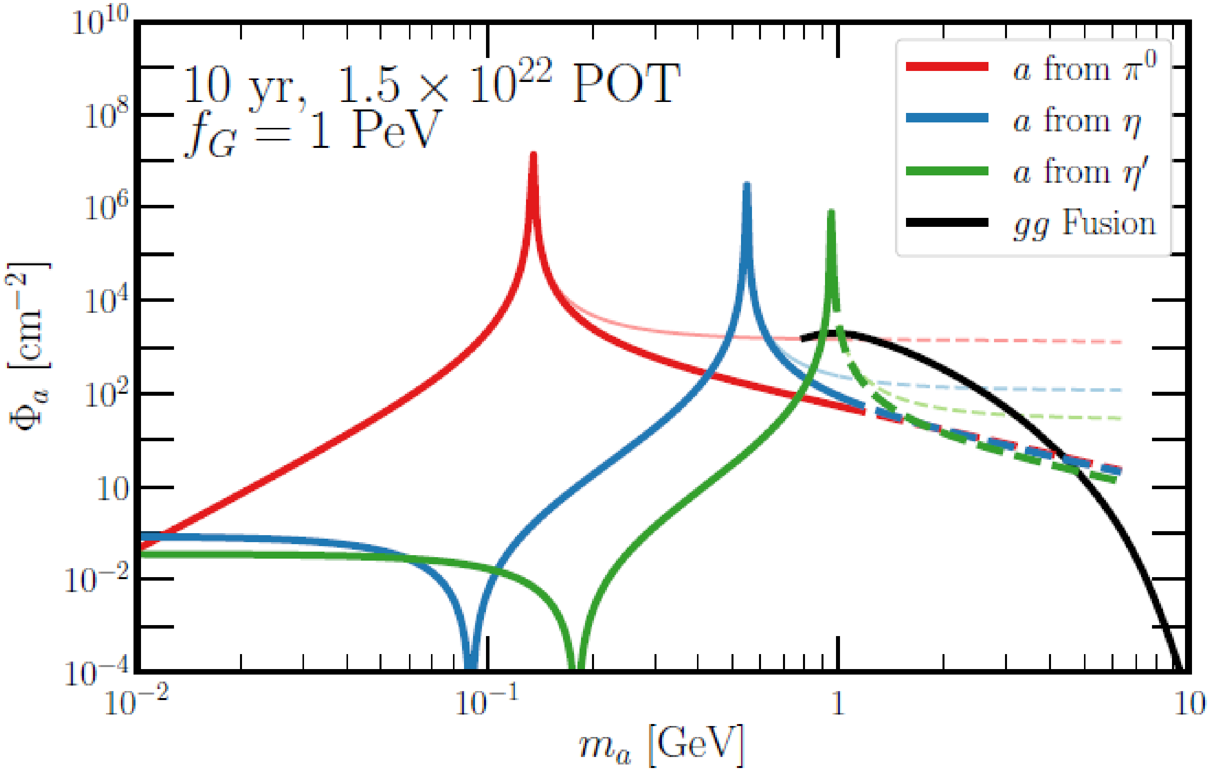
DUNE coverage



High-quality axion (or generic Axion-like-particles) shows an exciting opportunity for particle physics

But, do we really know the gluonic ALP production?





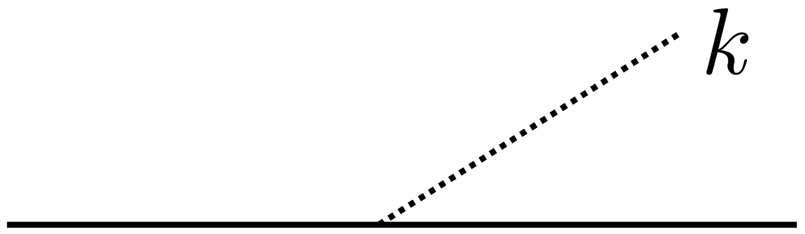
Gluonic ALP production reconsidered

On going work
Kunfeng Lyu, ZL

Meson decays, Mixing with Mesons, Hard Scattering, Parton splitting, Bremsstrahlung…

Forward ALP can be viewed as an ISR

ISR from partons, proton?



Parton bremming
(~ALP PDF)

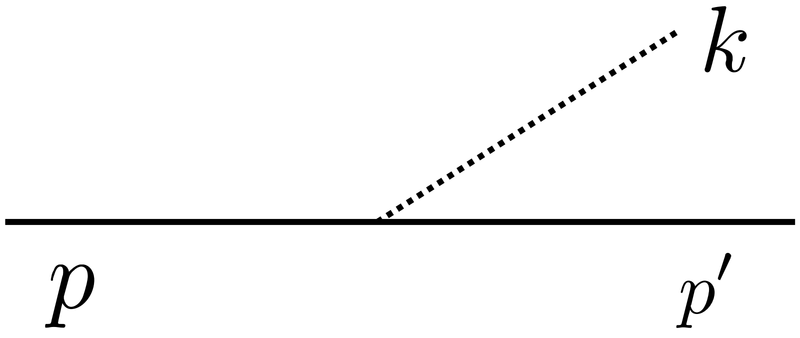
Proton bremming

Our (preliminary) result shows that the ISR signal from gluon and quark bremming far smaller than the parton bremming

Primary contribution.

Splitting Function

The signal rate for emitting an axion from the proton bremming



$$\sigma = \int dz dp_T^2 \frac{d\mathcal{P}}{dz dp_T^2} \hat{\sigma}_{\rm NSD}(\hat{s})$$

$$\frac{d\mathcal{P}}{dz dp_T^2} = \frac{1}{16\pi^2} \frac{z}{1-z} \frac{1}{(p'^2 - m_p^2)^2} \left[\frac{1}{2}\sum |\mathcal{M}|^2\right] F_S(k,p')^2$$

Form Factor

$$F_{pp^*a}(p'^2) = \frac{\Lambda^4}{\Lambda^4 + (p'^2 - m_p^2)^2}$$

$$\Lambda = 1 \sim 2\,\mathrm{GeV}$$

$$F_S(k,p') = F^a_{1,p}(k^2) F_{pp^*a}(p'^2)$$

Nucleon Form Factor

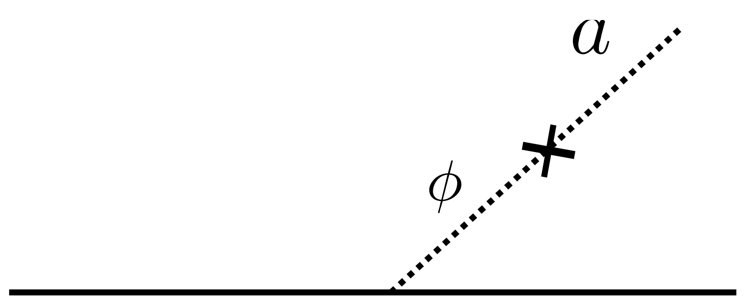
$$F_{1,p}(k^2)|_{\rm timlike} = \frac{1}{(1-\gamma e^{i\delta} k^2)^2} \left[1 - \alpha + \alpha \frac{m_{a_1}^2 (m_{a_1}^2 - k^2 + i m_{a_1} \Gamma_{a_1})}{\left(m_{a_1}^2 - k^2\right)^2 + m_{a_1}^2 \Gamma_{a_1}^2}\right]$$

Proton-ALP Coupling

Effective operator $\frac{C_p(m_a)}{2f_a}\bar{p}\gamma^\mu\gamma_5 p\,\partial_\mu a$

$$C_p(m_a) = C_p^0 + \sum_\phi \frac{C_{K,\phi} m_a^2}{m_a^2 - m_\phi^2}\frac{g_{\phi pp}}{m_p} - \sum_\phi \frac{C_{M,\phi} m_\phi^2}{m_a^2 - m_\phi^2}\frac{g_{\phi pp}}{m_p}$$

Kinetic mixing Mass mixing



$$g_{pa} = \frac{1}{2f_a}\left[\hat{c}_{uu}\left(D + D_s + F\right) + \hat{c}_{dd}D_s + \hat{c}_{ss}\left(D + D_s - F\right)\right]$$
$$+ \frac{1}{2f_a}\left[\left(D + F\right)\langle\pi a\rangle - \frac{1}{\sqrt{3}}\left(D - 3F\right)\langle\eta_8 a\rangle + \sqrt{\frac{2}{3}}\left(2D + 3D_s\right)\langle\eta_1 a\rangle\right]$$

$$\mathcal{L} \supset \mathrm{tr}\bar{B}\left(i\not{D}\right)B + \frac{D}{2}\mathrm{tr}\bar{B}\gamma_\mu\gamma_5\{u^\mu, B\} + \frac{F}{2}\mathrm{tr}\bar{B}\gamma_\mu\gamma_5[u^\mu, B] + \frac{D_s}{2}\mathrm{tr}\bar{B}\gamma_\mu\gamma_5 B\,\mathrm{tr}\,u^\mu$$

$D \approx 0.80, F \approx 0.46, D_s \approx -0.41$

$$\pi^0 \to \pi^0 + \langle\pi^0 a\rangle a + \langle\pi^0\eta_8\rangle\eta_8 + \langle\pi^0\eta_1\rangle\eta_1$$
$$\eta_8 \to \cos\theta_{\eta\eta'}\eta_8 + \sin\theta_{\eta\eta'}\eta_1 + \langle\eta_8 a\rangle a + \langle\eta_8\pi^0\rangle\pi^0$$
$$\eta_1 \to -\sin\theta_{\eta\eta'}\eta_8 + \cos\theta_{\eta\eta'}\eta_1 + \langle\eta_1 a\rangle a + \langle\eta_1\pi^0\rangle\pi^0$$

In the massless limit, matches known results (PDG)

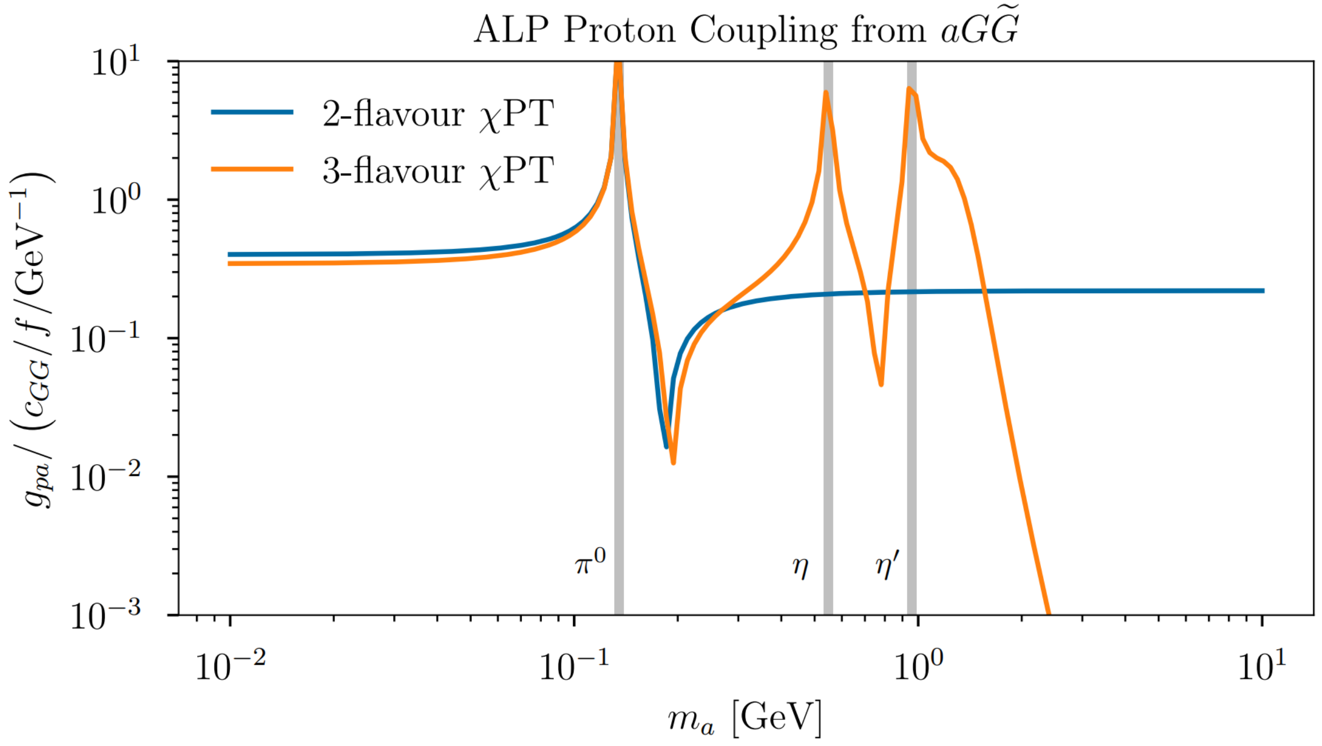
$$C_p = -0.47(3) + 0.88(3)C_u - 0.39(2)C_d - 0.038(5)C_s - 0.012(5)C_c - 0.009(2)C_b - 0.0035(4)C_t\,,$$
$$C_n = -0.02(3) + 0.88(3)C_d - 0.39(2)C_u - 0.038(5)C_s - 0.012(5)C_c - 0.009(2)C_b - 0.0035(4)C_t\,,$$

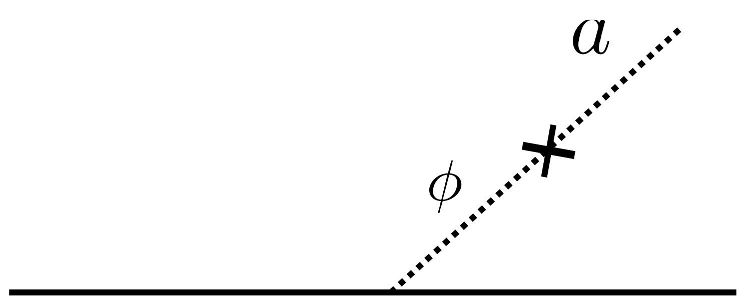
Proton-ALP Coupling

Effective operator $\frac{C_p(m_a)}{2f_a}\bar{p}\gamma^\mu\gamma_5 p\,\partial_\mu a$

$$C_p(m_a) = C_p^0 + \sum_\phi \frac{C_{K,\phi} m_a^2}{m_a^2 - m_\phi^2}\frac{g_{\phi pp}}{m_p} - \sum_\phi \frac{C_{M,\phi} m_\phi^2}{m_a^2 - m_\phi^2}\frac{g_{\phi pp}}{m_p}$$

Kinetic mixing Mass mixing

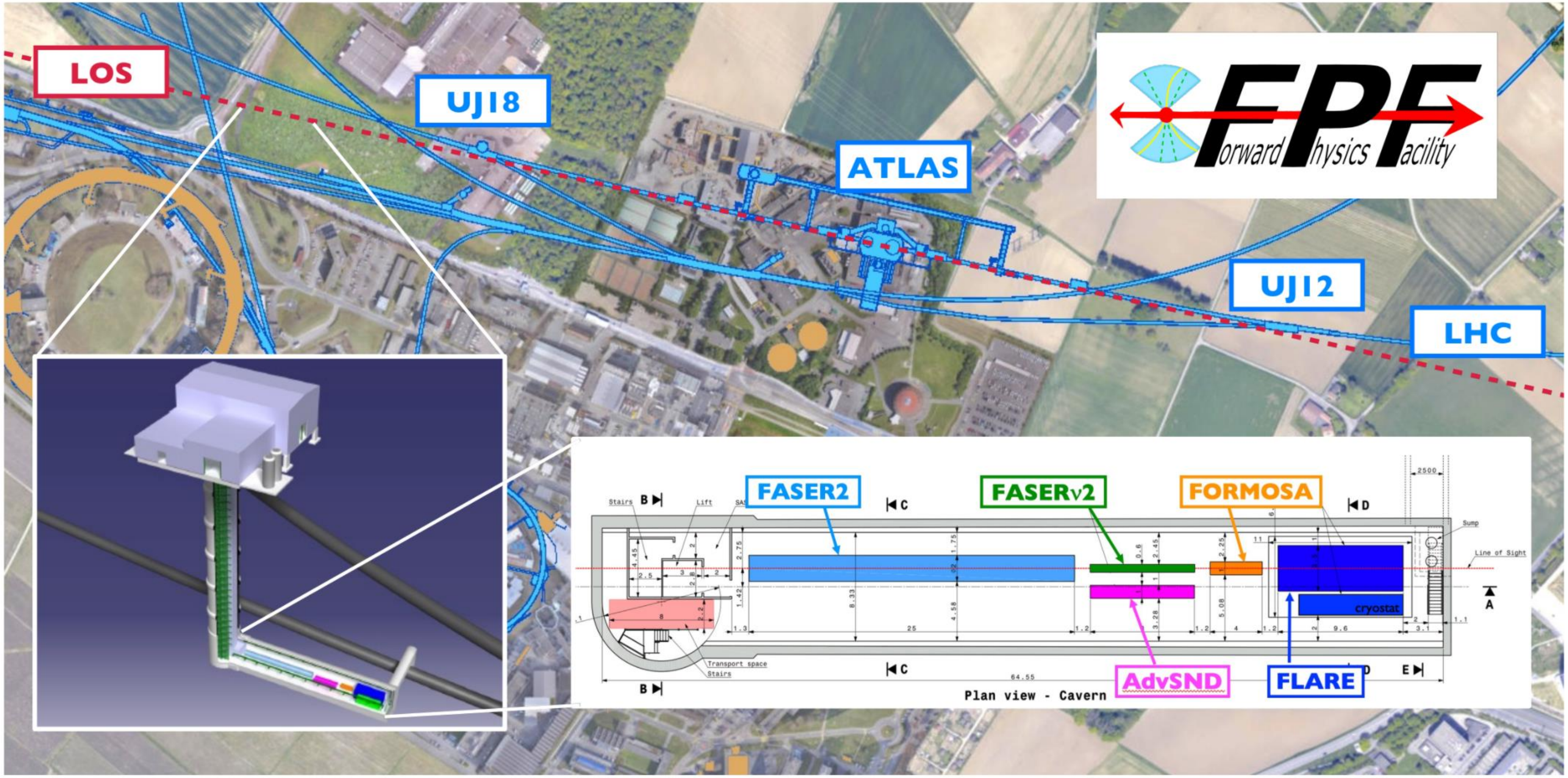




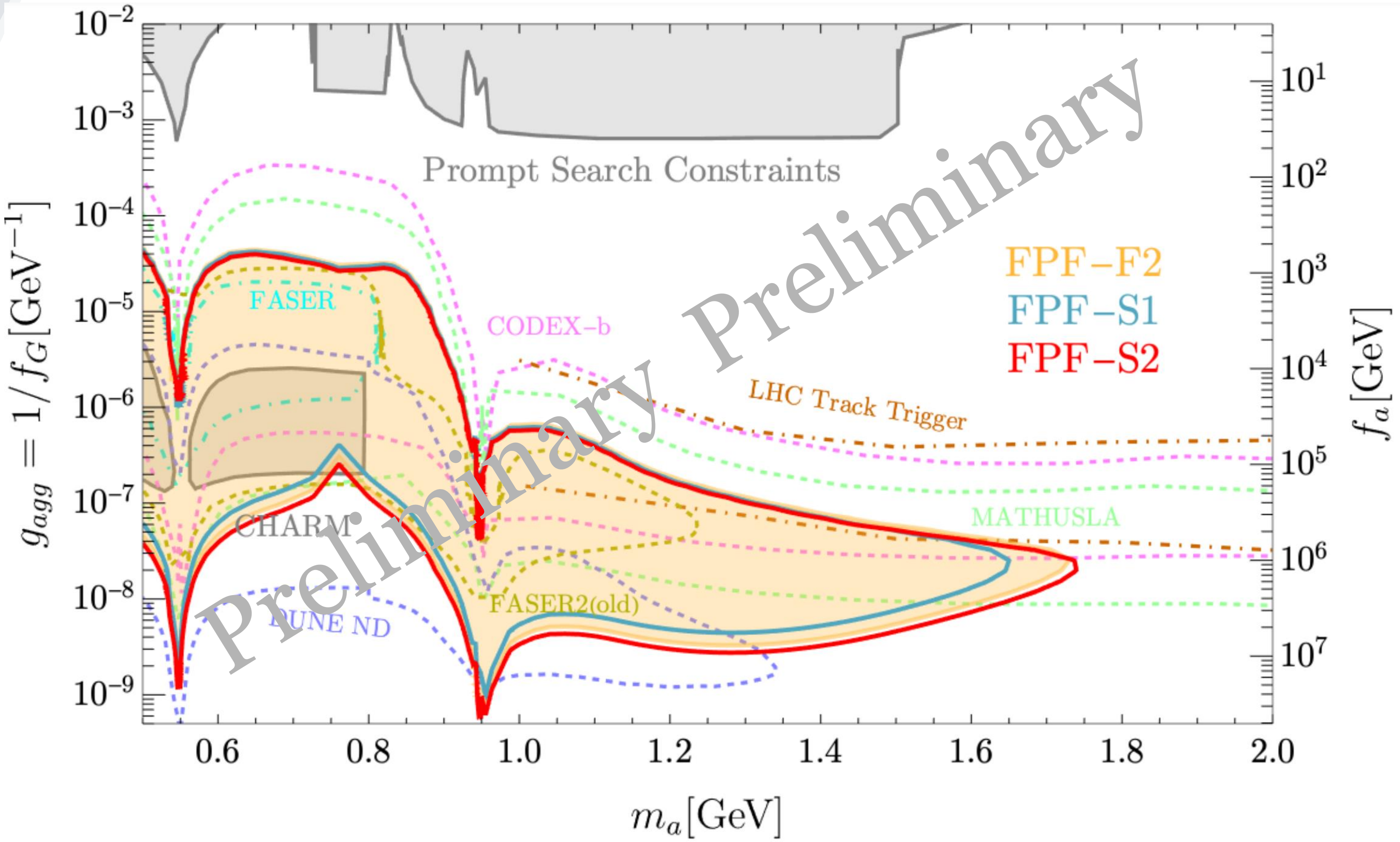
The scale-invariant part cancels with the kinetic mixing part in LO χPT in the large m_a limit.

See the discussion in N. Blinov, E. Kowalczk, M. Wynne, 2112.09814

Forward ALP productions impact: LHC Forward Detectors



New projections using proper production

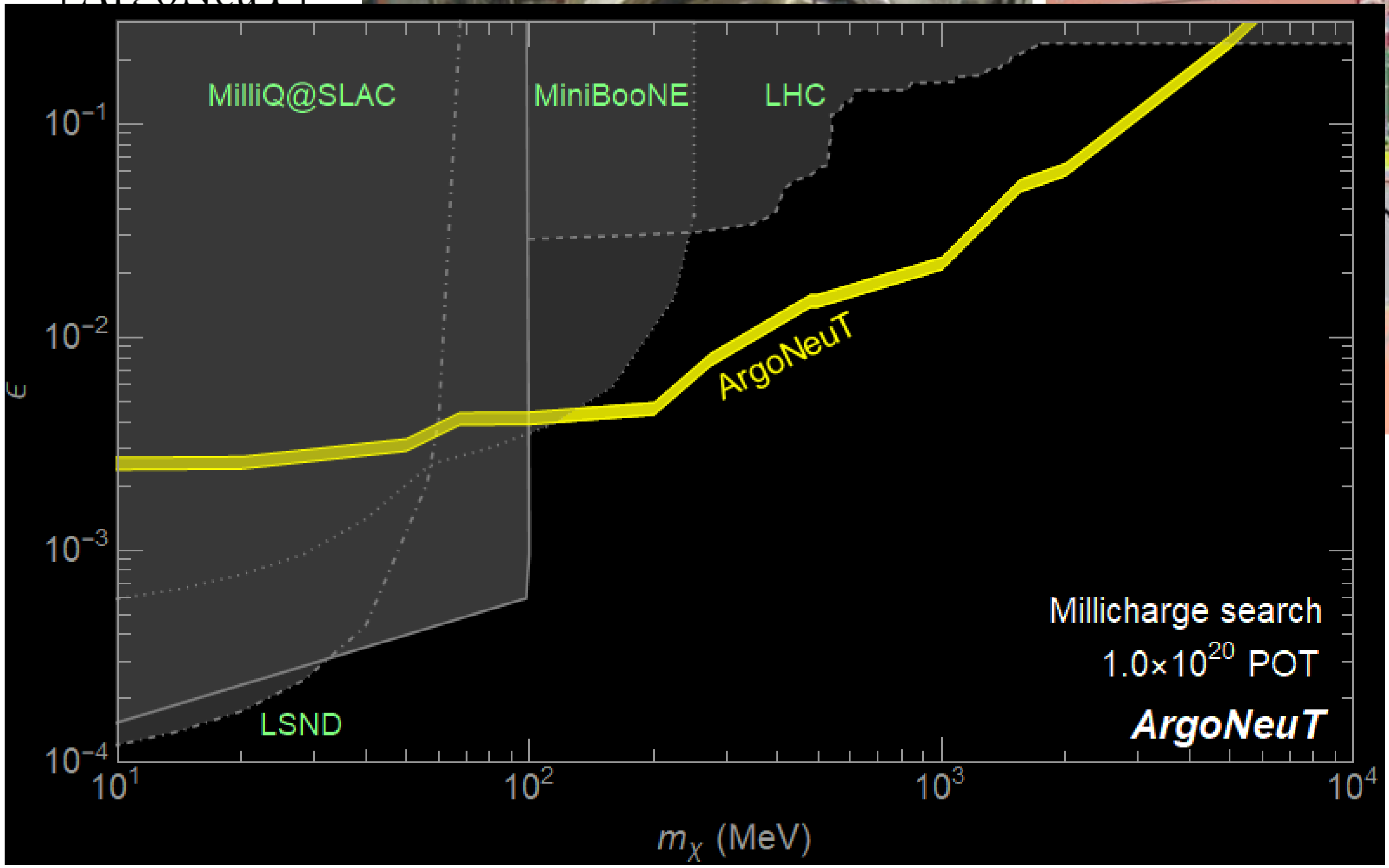


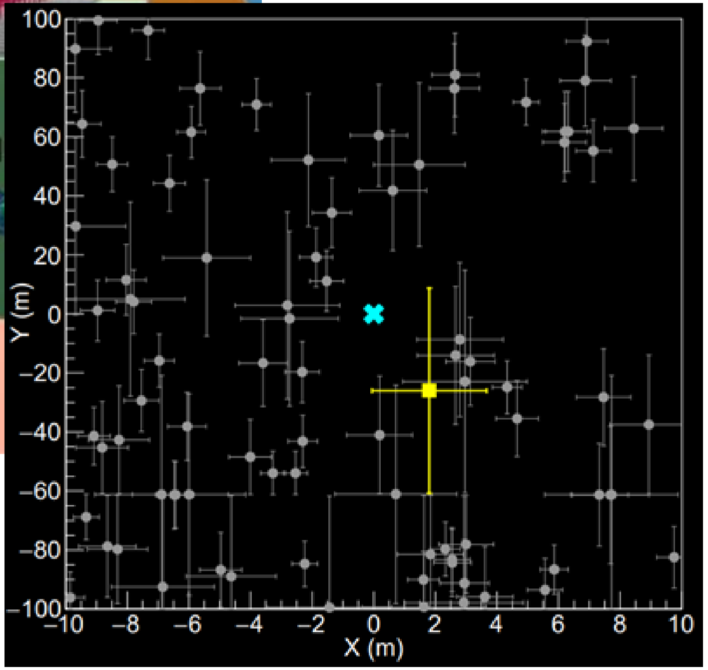
Kunfeng Lyu, ZL, in progress

Also included as part of the FPF report

DUNE ND: 2011.05995
FASER: 1806.02348
LHC Track: 1911.12364
FASER2: 1811.12522
CODEX-b: 1911.00481
MATHUSLA: 1606.06298

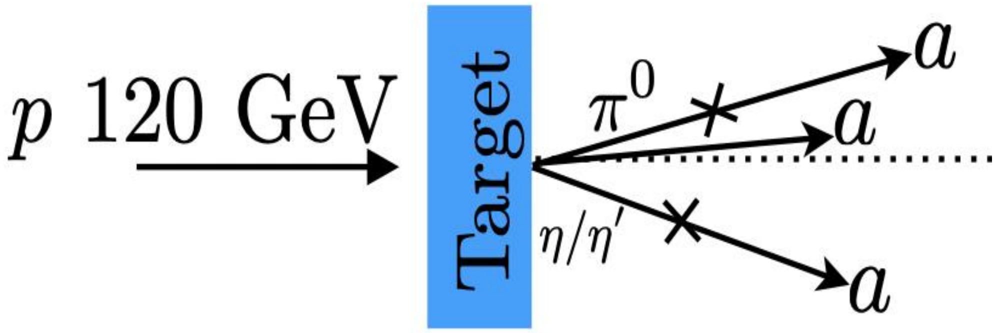
Can we do something with the existing data?





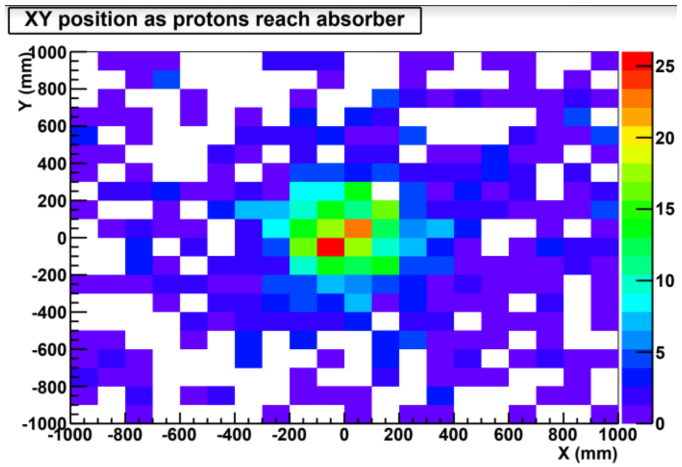
Harnik, ZL, Palamara, 19'
also with ArgoNeuT Collaboration, 19'

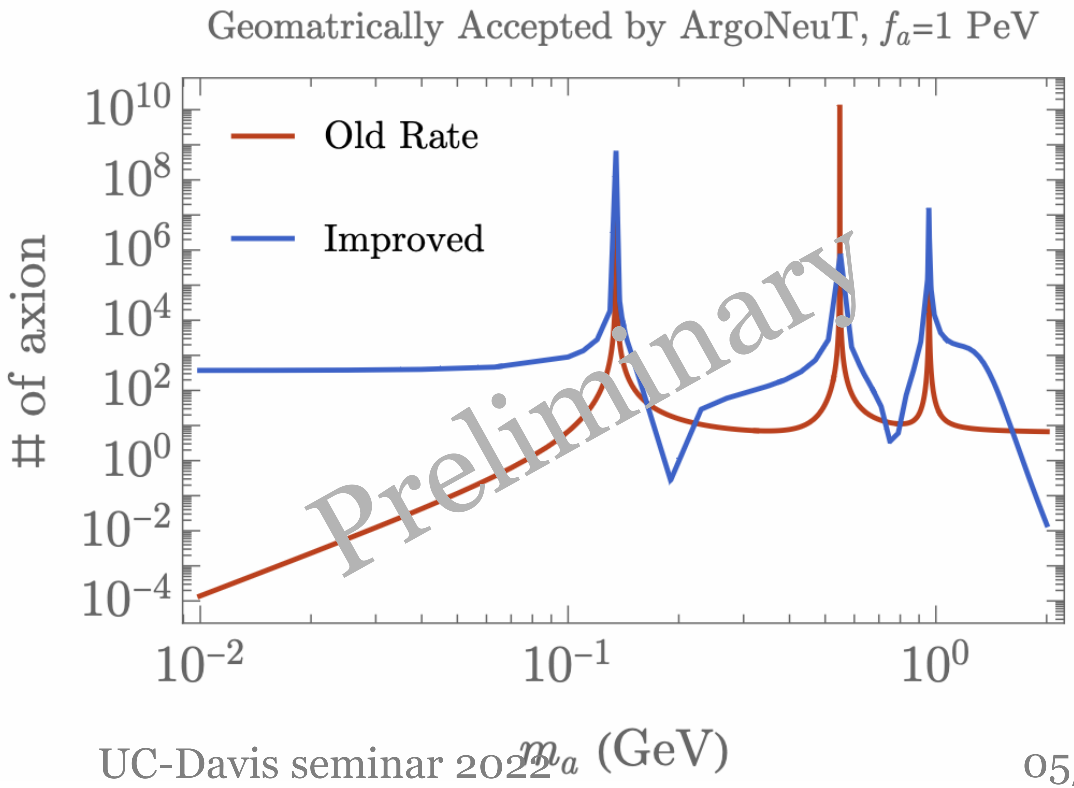
Production



ArgoNeuT

MINOS-ND



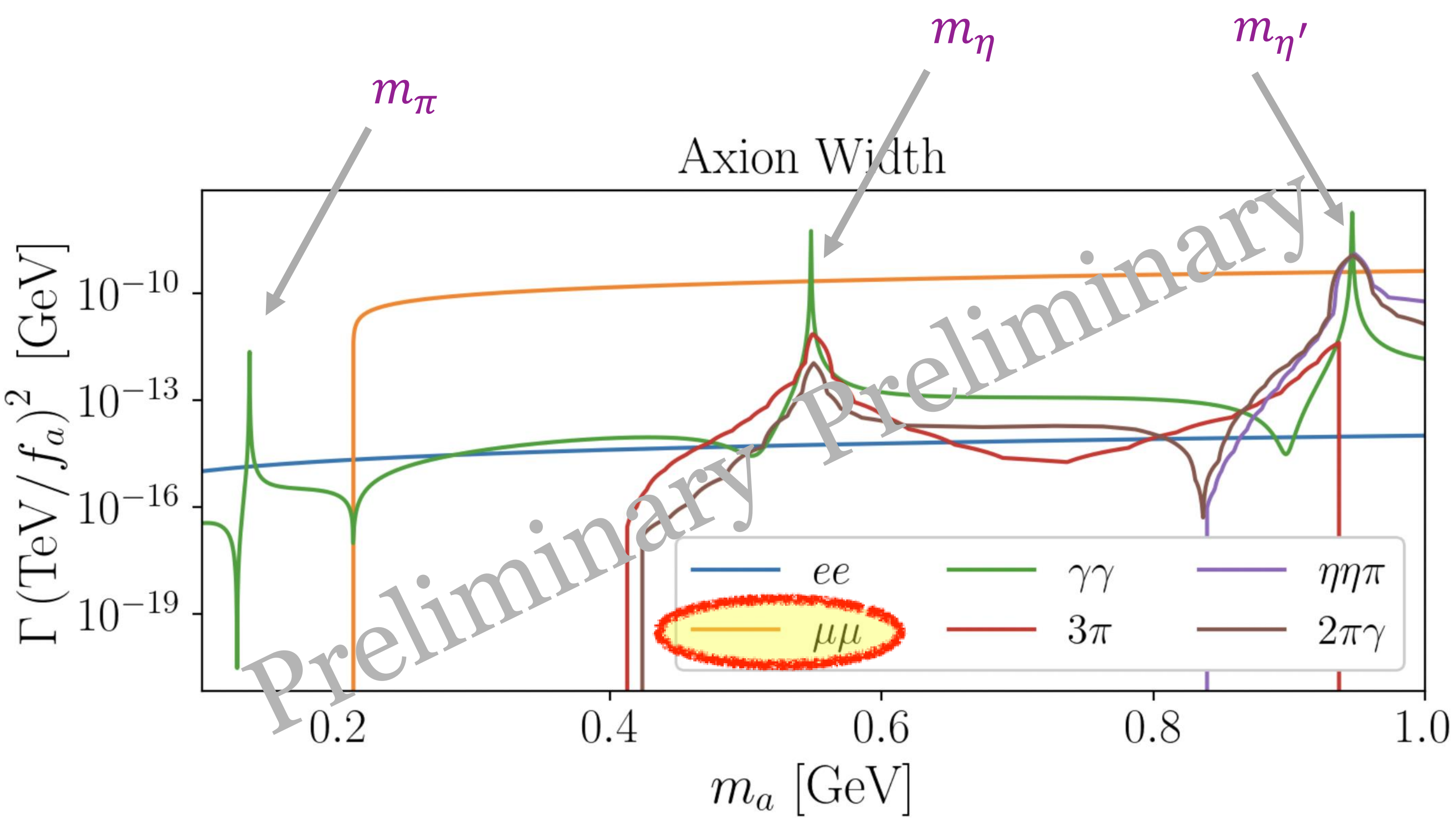


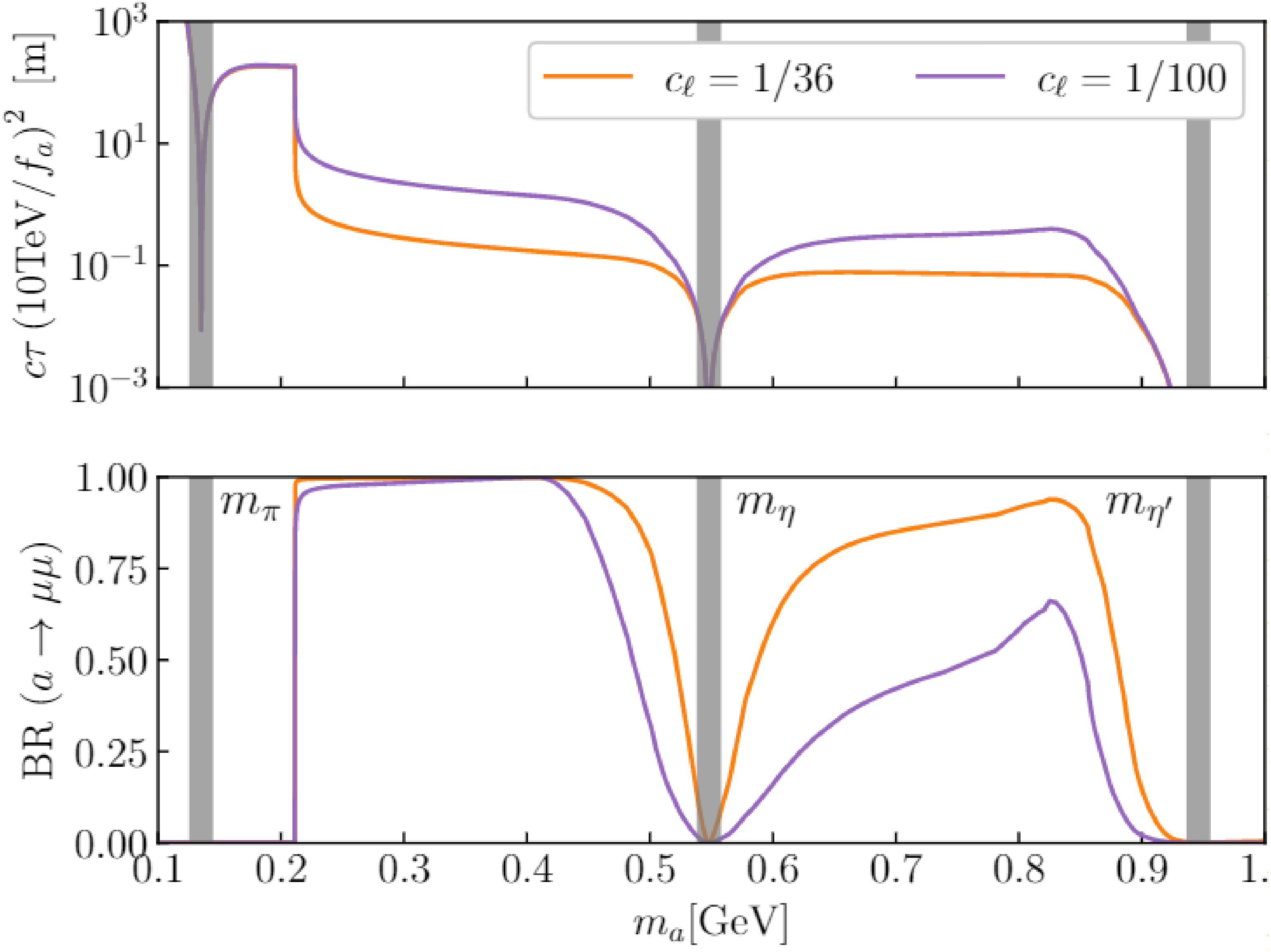
$$\mathcal{L}_{\rm gauge} = \frac{c_3\alpha_3}{8\pi f_a} aG\tilde{G} + \frac{c_2\alpha_2}{8\pi f_a} aW\tilde{W} + \frac{c_1\alpha_1}{8\pi f_a} aB\tilde{B}.$$

ArgoNeuT + MINOs can look for dimuons

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

- Dominated by 2μ decay

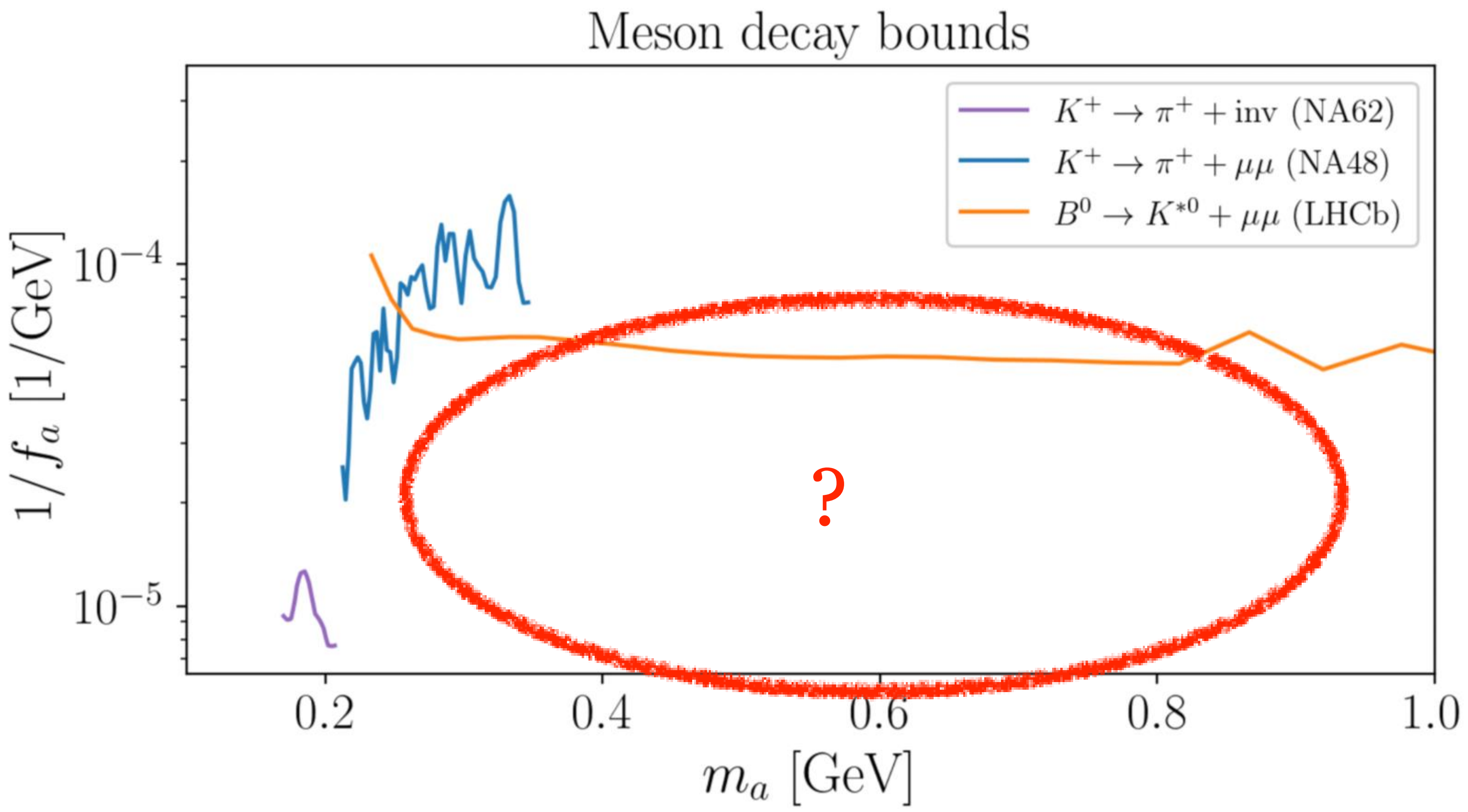




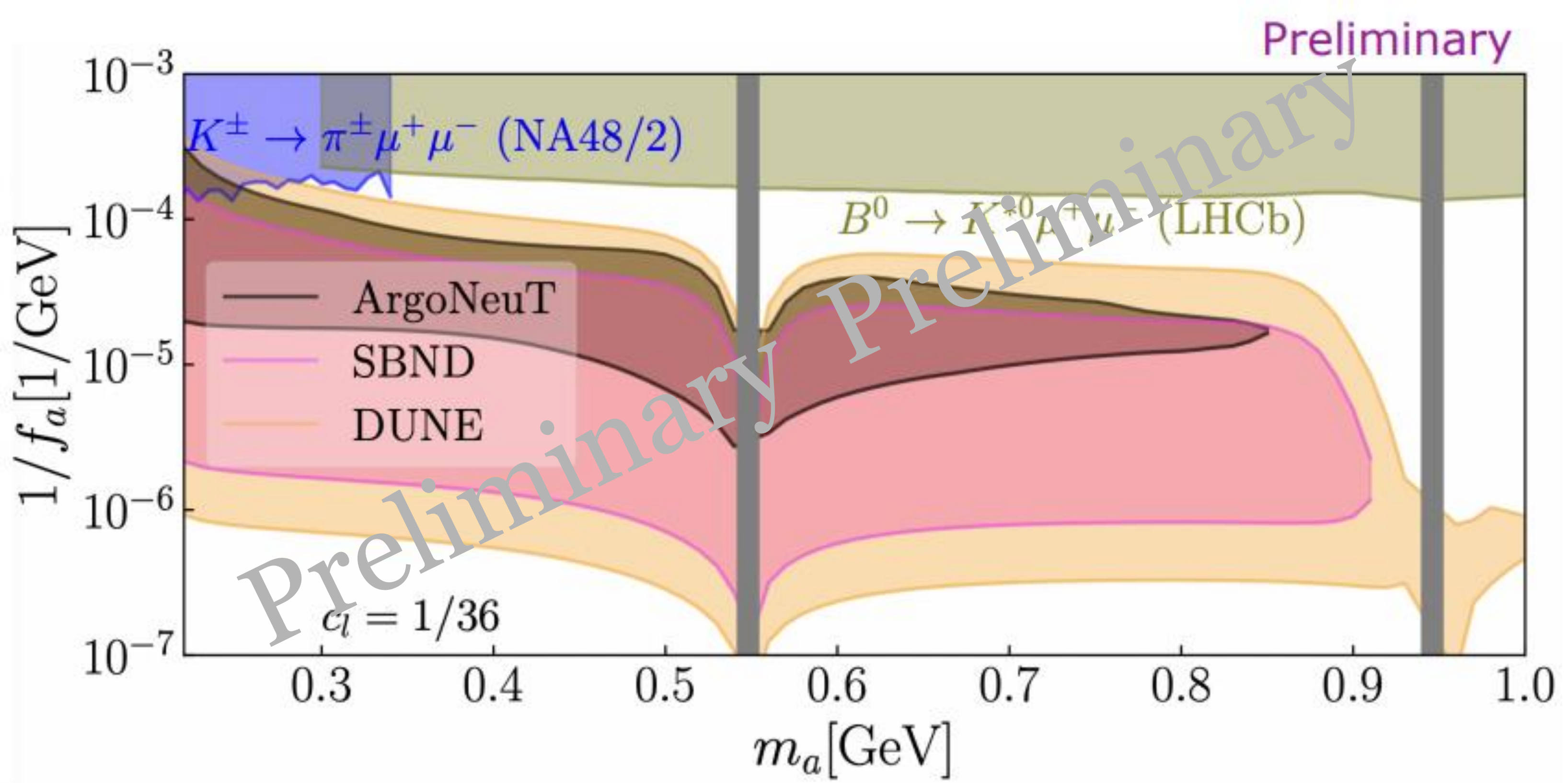
10^3
10^1
10^{-1}
10^{-3}
$c\tau\,(10\text{TeV}/f_a)^2$ [m]
$c_\ell = 1/36$
$c_\ell = 1/100$
1.00
0.75
0.50
0.25
0.00
BR $(a \to \mu\mu)$
m_π
m_η
$m_{\eta'}$
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.
m_a[GeV]

Constraints

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



Preliminary Results

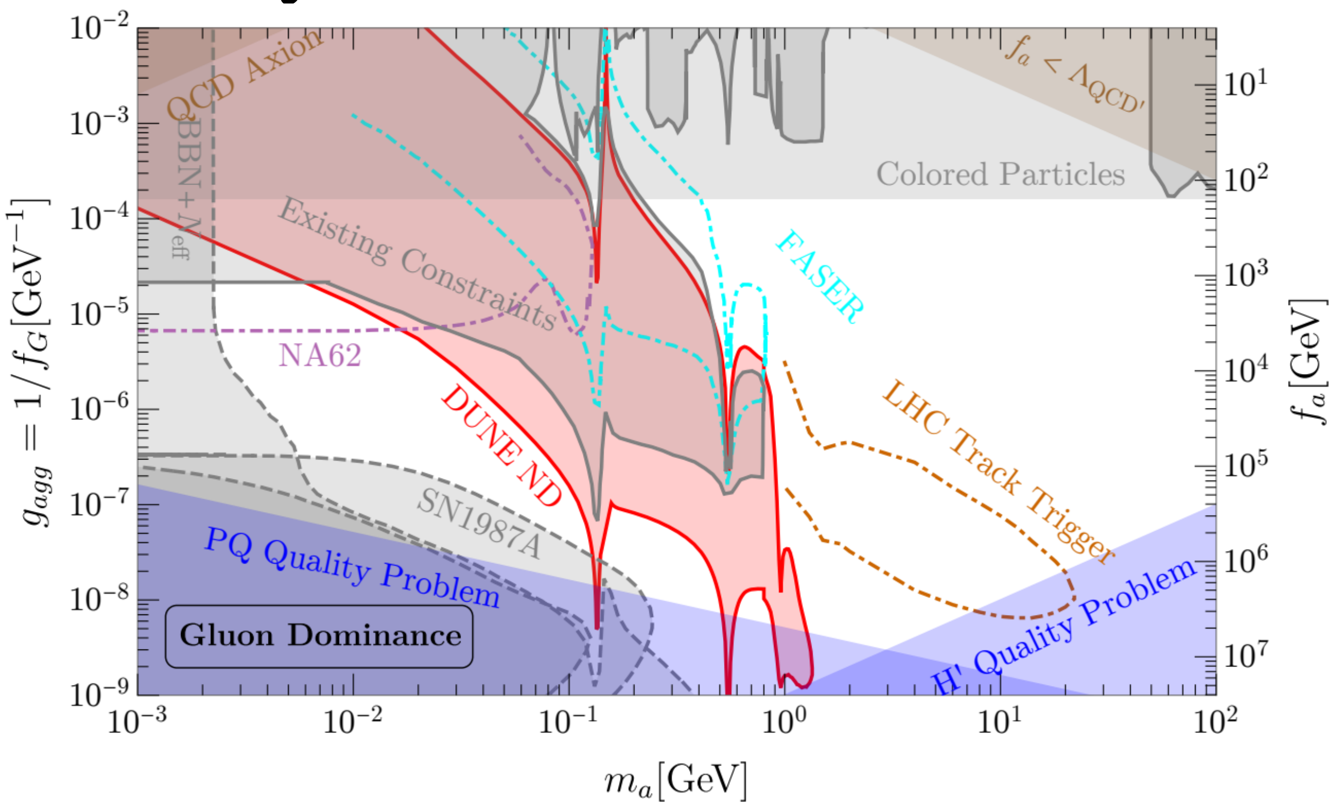


Existing data could put constraints on gluonic ALPs

Working with **S. Kumar, R. Co**, on theory studies on different future options.

Working with **ArgoNeuT** collaboration on reconstructions and putting out new results soon.

Summary and Outlook



- 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.

LHC (including FPF) and Neutrino experiments (DUNE, ArgoNeuT) will cover a large and unique parameter spaces of such motivated scenarios.

Thank you!

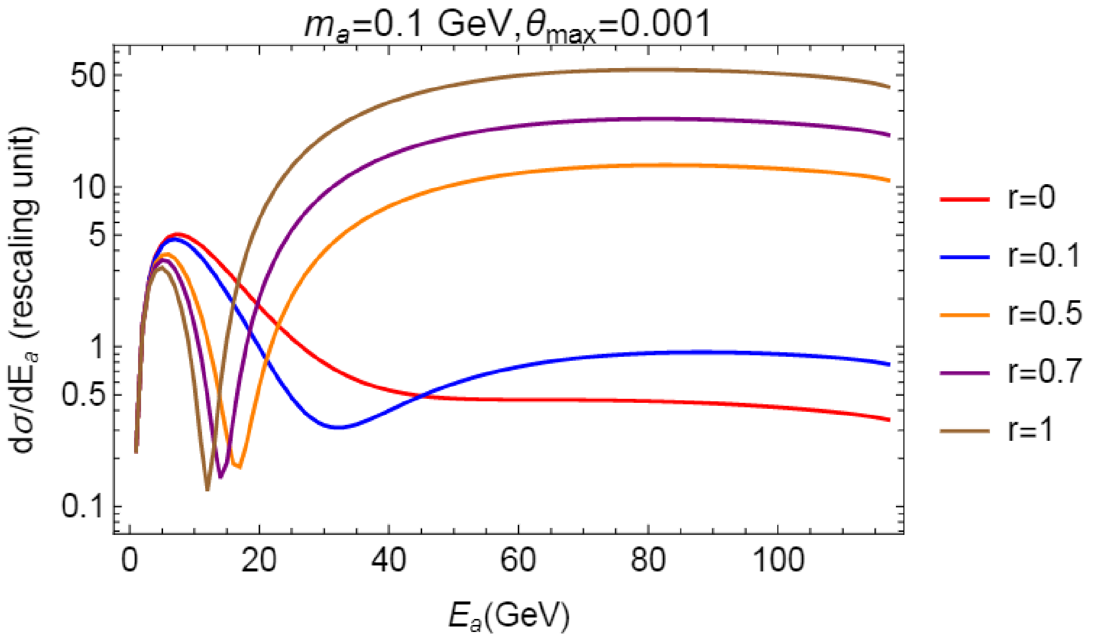
Matching Procedure and Momentum Shift-Scheme

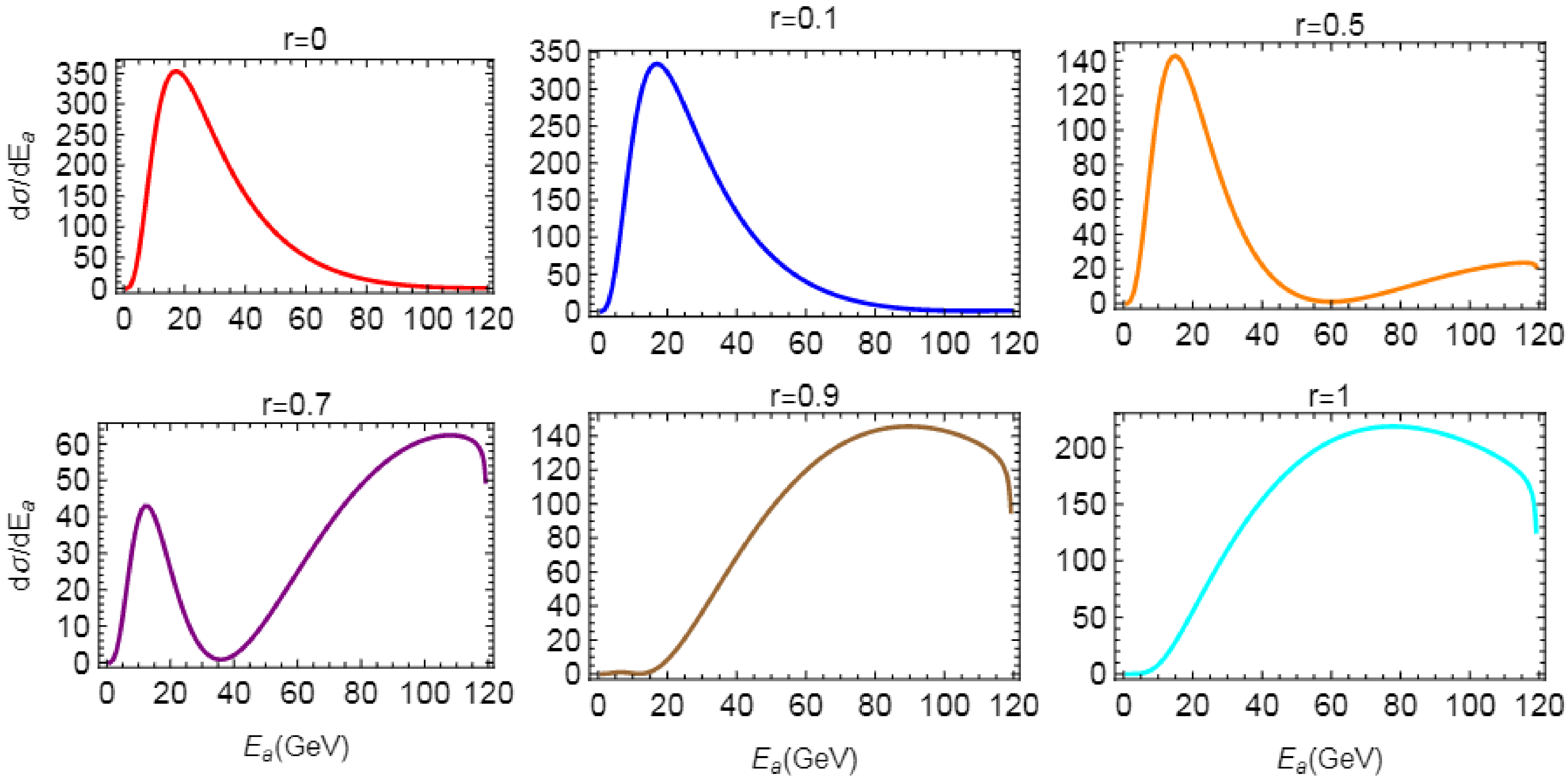
pseudo-scalar case

$$|\mathcal{M}|^2 = \left(\frac{c_{pa}}{2f_a}\right)^2 \left[-4\left(k\cdot p'_m\right)(k\cdot p) - 2m_a^2\left(p'_m\cdot p\right) - 2m_p^2 m_a^2\right]$$

scalar case

$$|\mathcal{M}|^2 = \left(\frac{c_{pa}}{2f_a}\right)^2 \left[-4\left(k\cdot p'_m\right)(k\cdot p) - 2m_a^2\left(p'_m\cdot p\right) + 2m_p^2 m_a^2\right]$$




r=0
r=0.1
r=0.5
r=0.7
r=0.9
r=1
dσ/dE_a
dσ/dE_a
E_a(GeV)
E_a(GeV)
E_a(GeV)