Phenomenology Studies of ANUBIS

Prospective Models

Dark Matter Models

- Many options with varying complexity
  - Number of particles
  - Number of parameter
  - Theoretically "complete"

1) Renormalizable interaction with small dimensionless coupling constant

Portals

2) Higher-dimensional operators suppressed by couplings Λ^{-n} (new energy scale of hidden sector)

[arXiv:1504.04855v1]

How does ANUBIS compare to other detectors?

What can ANUBIS uniquely do?

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Vector

BC1: Dark photon
BC2: Dark photon coupled to light DM
BC3: $m_X \to 0 \Rightarrow$ effective DM coupling (*millicharged particles*)

Scalar

BC4: Higgs-mixing
BC5: Higgs-mixing + pair-production

HNLs

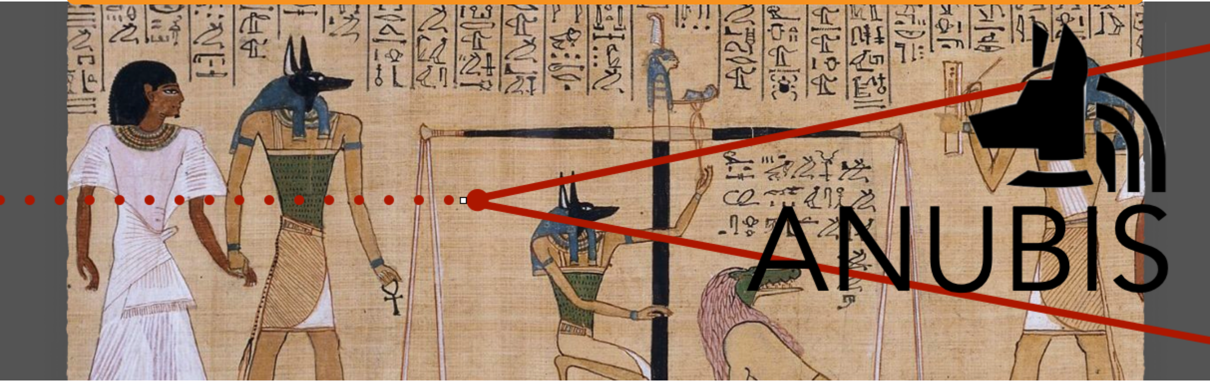
BC6: Electron neutrino mixing
BC7: Muon neutrino mixing
BC8: Tau neutrino mixing

Axion

BC9: ALP-photon coupling
BC10: ALP-fermion coupling
BC11: ALP-gluon coupling

FIPs 2022 Workshop Report Summary

Portals



- Mix dark photon with SM photon $\mathcal{L} \supset -\epsilon F_{\mu\nu} X^{\mu\nu}$ for $F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu$

  Problem: after Electroweak Symmetry Breaking (EWSB)
- Mix dark photon with hypercharge field $\mathcal{L} \supset \epsilon B_{\mu\nu} X^{\mu\nu}$ for $B_{\mu\nu} = \partial_\mu B_\nu - \partial_\nu B_\mu$

Vector Portal

$$\mathcal{L} \supset +\frac{1}{2}M_X^2 X_\mu X^\mu - \frac{1}{4}X_{\mu\nu}X^{\mu\nu} - \frac{\epsilon}{2\cos\theta_w}B_{\mu\nu}X^{\mu\nu} \tag{1}$$

$$\begin{pmatrix} W_\mu^3 \\ B_\mu \\ X_\mu \end{pmatrix} = \begin{pmatrix} \cos\theta_w & -\sin\theta_w & -\sin\theta_w\epsilon \\ -\sin\theta_w & \cos\theta_w & -\cos\theta_w\epsilon \\ \tan\theta_w\epsilon & 0 & 1 \end{pmatrix} \begin{pmatrix} Z_\mu \\ A_\mu \\ A'_\mu \end{pmatrix} \tag{2}$$

Mixing between B_μ, W_μ^3 and $X_\mu \Rightarrow \mathcal{L} \supset -\epsilon e j_{\text{EM}}^\mu A'_\mu$

[arXiv:2005.01515v3]

Scalar Portal

$$\mathcal{L} \supset -\left(\mu_S S + \lambda_S S^2\right) H^\dagger H \qquad (3)$$

Mixing between Higgs and dark scalar leads to coupling between dark scalar and Higgs SM interactions $\mathcal{O}_h$

$$\begin{pmatrix} h_1 \\ h_2 \end{pmatrix} = \begin{pmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} h \\ S \end{pmatrix}$$

$$\theta = \frac{\mu_S v}{m_h^2 - m_S^2} \qquad (4)$$

$$\theta S \times \sum_{\text{SM}} \mathcal{O}_h \qquad \Rightarrow \qquad \mathcal{O}_h = \frac{m_\psi}{v} \times \bar{\psi}\psi$$

Axion Portal

$$\mathcal{L} \supset + \frac{1}{2}(\partial_\mu a)(\partial^\mu a) - \frac{m_a^2}{2}a^2 + \sum_f \frac{c_{ff}}{2}\frac{\partial^\mu a}{f_a}\bar{f}\gamma_\mu\gamma_5 f$$
$$- \frac{a}{f_a}\left(c_{\tilde{B}} B_{\mu\nu}\tilde{B}^{\mu\nu} + c_{\tilde{W}} W^A_{\mu\nu}\tilde{W}^{\mu\nu,A} + C_{\tilde{G}} G^a_{\mu\nu}\tilde{G}^{a,\mu\nu}\right) \quad (5)$$

[arXiv:1701.05379v3]

$$\mathcal{L} \supset +\frac{1}{2}(\partial_\mu a)(\partial^\mu a) - \frac{m_a^2}{2}a^2 + \sum_f \frac{c_{ff}}{2}\frac{\partial^\mu a}{f_a}\bar{f}\gamma_\mu\gamma_5 f \tag{6}$$
$$- \frac{a}{f_a}\left(c_{\tilde{B}} B_{\mu\nu}\tilde{B}^{\mu\nu} + c_{\tilde{W}} W^A_{\mu\nu}\tilde{W}^{\mu\nu,A} + C_{\tilde{G}} G^a_{\mu\nu}\tilde{G}^{a,\mu\nu}\right)$$

Photon Coupling

$$-\frac{1}{4}g_{a\gamma\gamma} a F_{\mu\nu}\tilde{F}^{\mu\nu} \qquad \text{for} \qquad g_{a\gamma\gamma} = \frac{4}{f_a}\left(c_{\tilde{B}} c_\theta^2 + c_{\tilde{W}} s_\theta^2\right) \tag{7}$$

ANUBIS can't detect photons $\Rightarrow$ unnecessary extra parameters
Not including limits production modes

$$\mathcal{L} \supset +\frac{1}{2}(\partial_\mu a)(\partial^\mu a) - \frac{m_a^2}{2}a^2 + \sum_f \frac{c_{ff}}{2}\frac{\partial^\mu a}{f_a}\bar{f}\gamma_\mu\gamma_5 f \tag{8}$$
$$- \frac{a}{f_a}\left(c_{\tilde{B}} B_{\mu\nu}\tilde{B}^{\mu\nu} + c_{\tilde{W}} W^A_{\mu\nu}\tilde{W}^{\mu\nu,A} + C_{\tilde{G}} G^a_{\mu\nu}\tilde{G}^{a,\mu\nu}\right)$$

Gluon Coupling

$$-\frac{1}{4}g_{agg}\,aG^a_{\mu\nu}\tilde{G}^{a,\mu\nu} \qquad \text{for} \qquad g_{agg} = \frac{4}{f_a}c_{\tilde{G}} \tag{9}$$

Same as coupling to photons

$$\mathcal{L} \supset +\frac{1}{2}(\partial_\mu a)(\partial^\mu a) - \frac{m_a^2}{2}a^2 + \sum_f \frac{c_{ff}}{2}\frac{\partial^\mu a}{f_a}\bar{f}\gamma_\mu\gamma_5 f \\ - \frac{a}{f_a}\left(c_{\tilde{B}}B_{\mu\nu}\tilde{B}^{\mu\nu} + c_{\tilde{W}}W^A_{\mu\nu}\tilde{W}^{\mu\nu,A} + C_{\tilde{G}}G^a_{\mu\nu}\tilde{G}^{a,\mu\nu}\right) \tag{10}$$

Fermion Coupling

$$-\frac{ia}{f_a}\sum_{\psi=Q,L} g_{a\psi}m_\psi^{\text{diag}}\bar{\psi}\gamma^5\psi \tag{11}$$

Important coupling!

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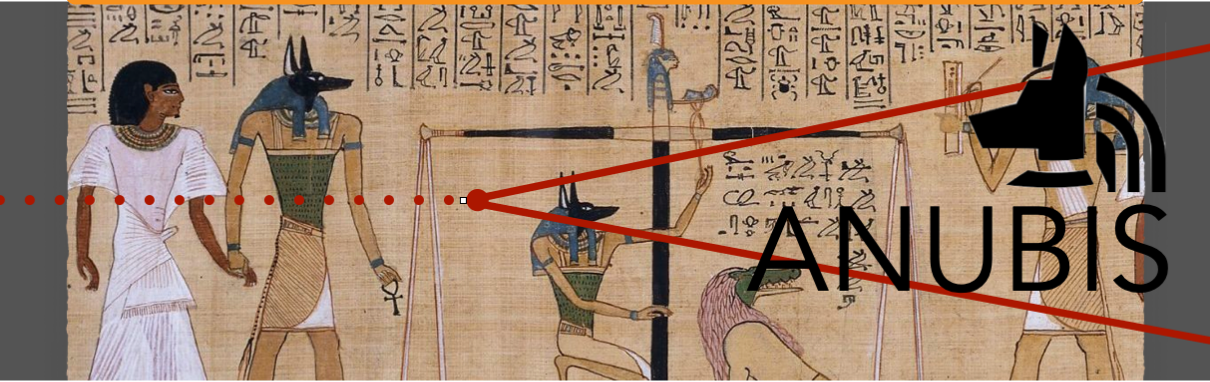
Parameters



Parameters

Physics Beyond Colliders/FIPs Benchmarks

Vector

BC1: Dark photon $\{m_X, \epsilon\}$

Scalar

BC4: Higgs-mixing $\{m_S, \theta\}$

BC5: Higgs-mixing + pair-production $\{m_S, \theta, \lambda\}\,(\lambda = 5 \times 10{-}4)$

HNLs

BC6: ν_e mixing $\{m_N, |U_e|^2\}$

BC7: ν_μ mixing $\{m_N, |U_\mu|^2\}$

BC8: ν_τ mixing $\{m_N, |U_\tau|^2\}$

Axion

BC10: ALP-fermion coupling $\{m_a, g_{a\psi}\}$

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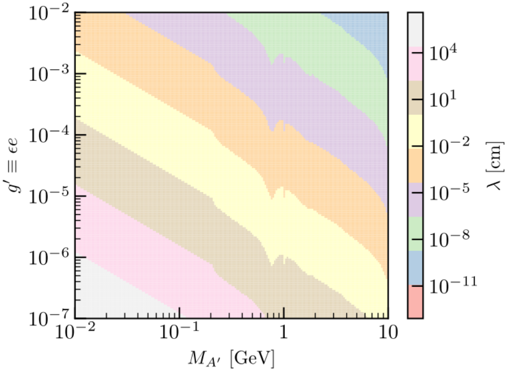
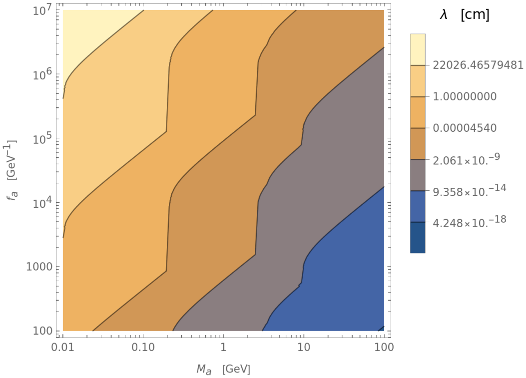
Considerations

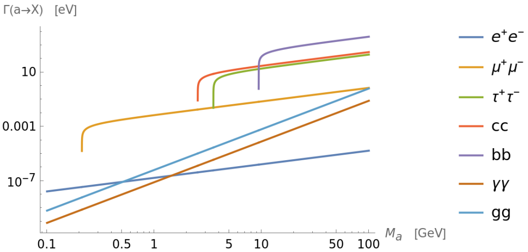
- Mass of Particle
  - Energy available (Processes)
- Coupling
  - Decay length



Decay length for $U(1)_{B-L}$ dark photon in $e^+e^- \to X\gamma$ [arXiv:2203.03280v2]



Decay length for ALP in $pp \to ALP\gamma\star$



Decay modes for ALP

$\star$ Following [arXiv:2203.03280v2], $|\vec{p}| = \frac{s - M_a^2}{2\sqrt{s}}$

Considerations

- Mass of Particle
  - Energy available (Processes)
- Coupling
  - Decay length
  - Implications on other processes/parameters

Mixing

Mixing Higgs w. dark scalar

Measured Higgs mass $\neq$ Higgs mass in $\mathcal{L}$

Hidden Abelian Higgs Model (HAHM)

FeynRules Model

- Contains a dark scalar & dark vector
- $M_{\text{dark vector}} \to 0$ or $\infty \Rightarrow$ Lots of couplings $\to \infty$
- Mixing $Z - Zd$: Couplings $\to \infty \Rightarrow$ Cannot disentangle

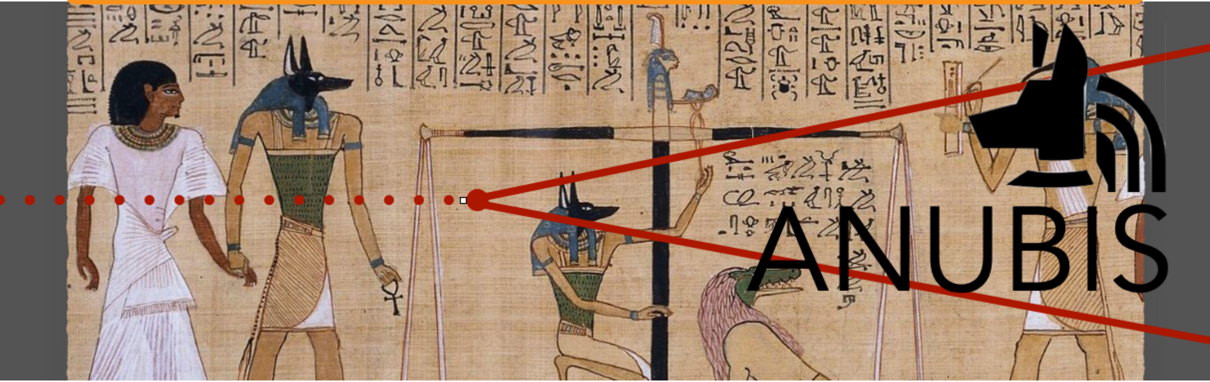
Have to be careful!

Framework

1) Import parameter definitions from FeynRules model
2) Separate external values & internal parameter
3) Expand internal parameter definitions in terms of only external values

$\longrightarrow$ Test external parameter values $\longleftarrow$

Status



HNLs

UFO model?
Pythia

Axion

FeynRules & UFO Model ✓
Easy to use, can switch on/off couplings

Vector & Scalar

Many models available, varying complexity

Make our own simplified version

Consideration:

1) Full SM modified
2) Simplified SM modified

Task: Repository (GitHub?) for UFO models

Vector

$m_X \in [10^{-3}, 10^{3}]$ GeV
$\epsilon \in [10^{-9}, 10^{-2}]$

Scalar

$m_S \in [10^{-2}, 10^{2}]$ GeV
$\sin^2\theta \in [10^{-14}, 10^{-1}]$

$\star$ v: the SM Higgs vev

HNLs

$m_N \in [10^{-2}, 10^{2}]$ GeV
$|U_e|^2 \in [10^{-12}, 10^{-2}]$
$(|U_\mu|^2, |U_\tau|^2) \in [10^{-11}, 10^{-2}]$

Axion

$m_a \in [10^{-2}, 10]$ GeV
$g_Y = \frac{2v\star}{f_a} \in [10^{-14}, 10^{-1}]$

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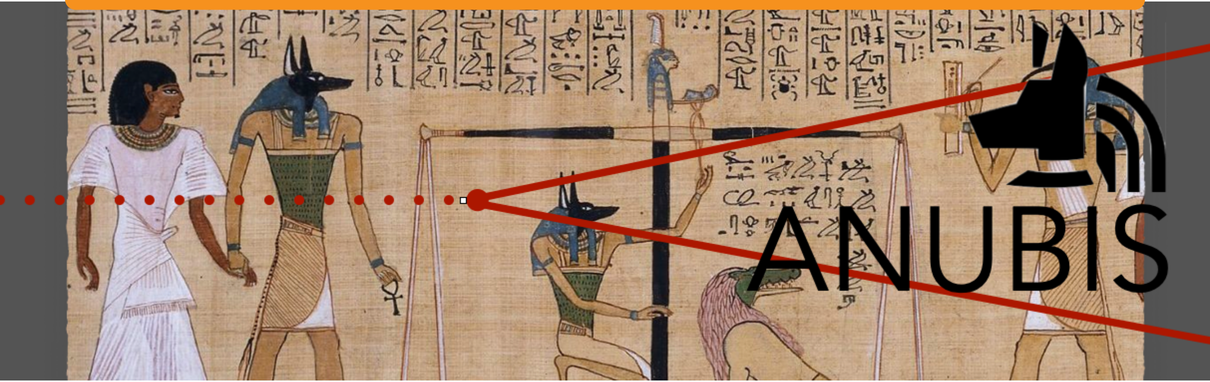
Plan

- Identify production processes
  - $\Rightarrow$ Characteristic momenta/energy
- Calculate decay length from decay modes
  - $\Rightarrow$ Window for DM mass & coupling
- MadGraph Simulations & ANUBIS Geometry
- (Investigate contributions for processes)

Further Study



How does ANUBIS compare to other detectors?

What can ANUBIS uniquely do?

Charging fermions under new $U(1)_X$

$$\mathcal{L} \supset -g_X j_\mu^X X^\mu \tag{12}$$

$$j_\mu^X = 0 \qquad U(1)_X$$

$$j_\mu^{i-j} = \bar{L}_i \gamma_\mu L_i + \bar{l}_i \gamma_\mu l_i - \bar{L}_j \gamma_\mu L_j + \bar{l}_j \gamma_\mu l_j \qquad U(1)_{L_i - L_j}$$

$$j_\mu^{B-L} = \frac{1}{3}\bar{Q}\gamma_\mu Q + \frac{1}{3}\bar{u}_R \gamma_\mu u_R + \frac{1}{3}\bar{d}_R \gamma_\mu d_R + \bar{L}\gamma_\mu L - \bar{l}\gamma_\mu l - \bar{\nu}_R \gamma_\mu \nu_R \qquad U(1)_{B-L}$$

$i \neq j = e, \mu, \tau$

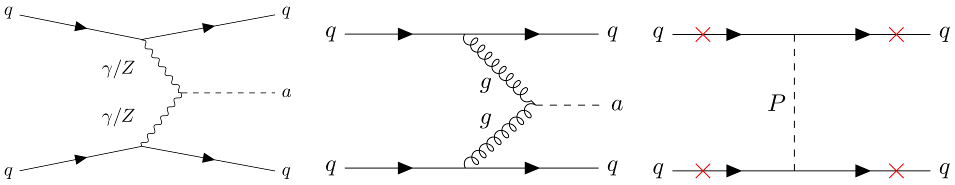
[arXiv:1504.04855v1]

$U(1)_X$ with new dark scalar which gives dark photon mass
(additional 3 right-handed neutrinos for completeness.)

Gauge group	q_L^i	u_R^i	d_R^i	ℓ_L^i	e_R^i	N_R^i	H	Φ
$SU(3)_C$	$\mathbf{3}$	$\mathbf{3}$	$\mathbf{3}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$
$SU(2)_L$	$\mathbf{2}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{2}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{2}$	$\mathbf{1}$
$U(1)_Y$	$1/6$	$2/3$	$-1/3$	$-1/2$	-1	0	$1/2$	0
$U(1)_X$	$\frac{1}{6}x_H + \frac{1}{3}x_\Phi$	$\frac{2}{3}x_H + \frac{1}{3}x_\Phi$	$-\frac{1}{3}x_H + \frac{1}{3}x_\Phi$	$-\frac{1}{2}x_H - x_\Phi$	$-x_H - x_\Phi$	$-x_\Phi$	$-\frac{x_H}{2}$	$2x_\Phi$

Particle content ($x_H = 0$ & $x_\Phi = 1$ is $U(1)_{B-L}$)

[arXiv:2104.10902]



Diagrams for axion production for P = h, a, γ, g, Z and × = axion emission

Signals

Can we distinguish these signals and allow for more than one coupling present?

Specific processes

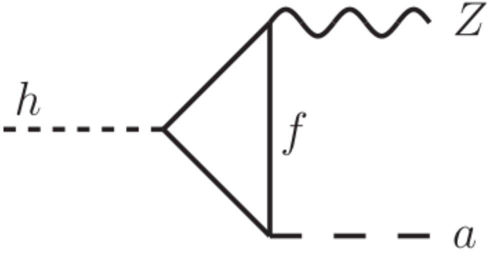


Diagram for Higgs-axion coupling

[arXiv:1708.00443v2]