Higgs-Electroweak Portal to the Dark Sector

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Higgs 2022, PISA

2110.10691 w/ H-C. Cheng and E. Salvioni

See also:
1803.03561 w/ H-C. Cheng, E. Salvioni and C. Verhaaren
1905.02198 w/ H-C. Cheng, E. Salvioni and C. Verhaaren
Irrelevant Portal to Hidden Valley

\[ \mathcal{L}_{\text{portal}} = \frac{\kappa \phi}{\Lambda_{\text{UV}}^{\Delta \phi - 2}} \phi H^\dagger H + \frac{\kappa J}{\Lambda_{\text{UV}}^2} J^D S J^\mu_{\text{SM}} + \frac{\kappa T}{\Lambda_{\text{UV}}^4} T^{\mu \nu}_{DS} O^S_{\mu \nu} \ldots \]

A general form

Suppressed HV-SM coupling from the \(~\text{TeV}\) scale

Other possibilities include:
Higgs/dark photon/SM photon/axion portals
[S. Knapen, J. Shelton, D. Xu 2103.01238]
[G. Albouy et al, 2203.09503]
Irrelevent Portal Dark Pions

\[ - \mathcal{L}_{\text{UV}} = \overline{Q}_L Y \psi_R H + \overline{Q}_R \tilde{Y} \psi_L H + \overline{Q}_L M Q_R + \overline{\psi}_L \omega \psi_R + \text{h.c.}, \]

Q heavier than \( O(\text{TeV}) \)

\( H \)
\( Y \)
\( \psi \): Light SM singlet dark quarks

\( H \)
\( Y \)
\( Q \): Heavy SM doublet mediators

Small mass, dark pions can be very light \((< \text{GeV})\)

\( \omega, M, Y, \tilde{Y} \): N×N mass/Yukawa matrixes

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Irrelevent Portal Dark Pions (II)

\[ \mathcal{L}_{\text{EFT}} = \frac{1}{2} \bar{\psi}_R Y^\dagger M^{-2} Y \left[ |H|^2 i\not{D} + i\gamma^\mu H^\dagger D_\mu H \right] \psi_R + \text{h.c.} \\
+ \frac{1}{2} \bar{\psi}_L \tilde{Y}^\dagger M^{-2} \tilde{Y} \left[ |H|^2 i\not{D} + i\gamma^\mu H^\dagger D_\mu H \right] \psi_L + \text{h.c.} \\
- \bar{\psi}_L \omega \psi_R + \bar{\psi}_L \tilde{Y}^\dagger M^{-1} Y \psi_R |H|^2 + \text{h.c.}, \]

Dimension-6 Z portal couplings

Dimension-5 Higgs portal coupling

\[ \omega, \frac{Y \tilde{Y} v^2}{M} \ll \Lambda \quad \rightarrow \quad (N^2 - 1) \text{ pNGBs} \]

In the special case \( N_{\text{flavor}} = 1 \), no isospin symmetry, thus no pNGBs, the dark sector has a heavy pseudoscalar (P), a vector (V) and a scalar (S) as ground states with comparable masses.
The Cartoon of Dark Spectrum

SM

mass

Dark QCD

$Q_{L,R}$

$\gamma \psi_1 \quad \psi_2 \leftarrow$

Dark Pions + ...

$\psi_{L,R}$

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Two Flavor, Three Dark Pions

Dark pions rearrange into CP eigenstates (like $K_S$ and $K_L$ in the SM)

The $\pi_2$ mix with the Higgs since it’s CP-even, with mixing angle:

$$s_\theta^{(2)} \sim 2\pi f_\pi^2 \frac{v}{m_h^2} \frac{Y\tilde{Y}}{M} \sim 10^{-6} \left( \frac{YY/\sqrt{M}}{10^{-2} \text{ TeV}^{-1}} \right) \left( \frac{f_\pi}{\text{GeV}} \right)^2$$

The $\pi_1$ and $\pi_3$ decay via Z portal, ALP-like (axion-like-particle) with large ALP decay constants:

$$f_\alpha \sim \frac{M^2}{Y^2 f_\pi} \quad \text{or} \quad \frac{M^2}{\tilde{Y}^2 f_\pi} \sim 1 \text{ PeV}$$

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Dark Pion Decays (ALP-Like)

Result applies to generic flavor diagonal ALP couplings

$m_{\pi} < m_{\eta'}$: dimuon mode dominates

$m_{\pi} > m_{\eta'}$: PPP modes (mostly SM $\pi^+\pi^-\pi^0$)

See also [D. Aloni, Y. Soreq and M. Williams, 1811.03474],

SM isospin suppressed modes

Elaborate discussions on indirect and ALP-type constraints in backup slides and the paper, e.g. flavor probes. See also Jure Zupan’s talk.

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Dark Pion from SM FCNC

Although suppressed by CKM and loop, still relevant since $\Gamma_{B,K}$ are suppressed by $(M_W)^{-4}$ in SM.

$$\mathcal{L}_{\text{eff}} \sim d_L \alpha d_L \beta \bar{\psi}' \psi', \quad \alpha < \beta$$

Amplitude can be fully adapted from $d_s \rightarrow \nu \nu$ results in [Inami, Lim 1980]

The four-fermion interaction then followed by the factorization

$$\langle \pi^a X | \mathcal{H}_{\text{eff}} | B \rangle = \langle \pi^a | X | \mathcal{H}_{\text{eff}} | 0 \rangle | B \rangle = \frac{ig^2}{64\pi^2} V_{ts}^* V_{tb} \langle X | \bar{s}_L \gamma\mu b_L^* | B \rangle \frac{p_\pi^\mu}{f_\pi^{(a)}} \left[ \frac{m_t^2}{m_W^2} \left( \log \frac{M^2}{m_t^2} - 2 \right) + 3 \right]$$

Finite terms introduces a numerical suppression $\sim 3$

$$\text{BR}(B^{+,0} \rightarrow \{K^+ \pi_b, K^{*0} \pi_b\}) \approx \{0.92, 1.1\} \times 10^{-8} \left( \frac{10^3 \text{ TeV}}{f_\pi^{(b)}} \right)^2 \{\lambda_{K\pi}^{1/2}, \lambda_{K^{*}\pi}^{3/2}\}$$

Experimentally achievable if dark pions are LLP
Current FCNC Bounds (B,K decay)

The bound as long as the experimental $E_{cm}$ > the BB/KK thresholds.

Limits coming from LHC, ee colliders and beam dump experiments.

Probing $f_a \sim \text{PeV}$ already.

Reaching $O(8-60)\ PeV$ for future experiments.

$\text{BR}(K^+ \to \pi^+ \pi^{(b)}) \approx 3.9 \times 10^{-11} \left(\frac{10^3 \, \text{TeV}}{f_a^{(b)}}\right)^2 \lambda_{\pi \pi}^{1/2}$

Kaon FCNC + LLP mode probes $f_a \sim \text{PeV}$ also. [NA48/2 1612.04723]
If any dark pion is an LLP → The case often referred to as “emerging jets”

[P. Schwaller, D. Stolarski and A. Weiler, 1502.05409]
[CMS, 1810.10069]
Example: Dimuon Search @ LHCb

Most straightforward strategy: if dark pion decays to dimuon largely, simply count the number of displaced dimuon vertexes.

Two peaks from benchmark pion width ratio 1:37

Sensitive to $f_{\pi}$ and $f_a$

2DV or beyond suffer from low vertex efficiency.

Data from [LHCb 2007.03923]

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Limits from the CMS data scouting [CMS, CMS-PAS-EXO-20-014]

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Summary

➢ Dark mesons are common and well motivated. From simple UV structures, there will be rich phenomenology.

➢ Easily long-lived. Dedicated calculations below the cc threshold.

➢ Phenomenology from current data shows that an M ~ a few TeV is achievable. Bright future prospects.

➢ Open fields (alternative portals, cosmology…) remain to be fully explored.
Backup Slides
Motivating Scenario I: Neutral Naturalness
Top partners gauged under hidden SU(3) to avoid strong bounds

Folded SUSY
[G. Burdman, Z. Chacko, H.S. Goh and R. Harnik, 0609152]

See also Tripled Top (TT) model
[H-C. Cheng, LL, E. Salvioni, and C. Verhaaren, 1803.03561]

Twin Higgs
[Z. Chacko, H.-S. Goh, and R. Harnik, 0506256]

Motivating Scenario II: Relaxion
The hidden SU(3) confinement generates the necessary backreaction potential
If the potential comes from the dark sector, the model avoids strong CP bounds.
[O. Antipin and M. Redi, 1508.01112][H. Beauchesne, E. Bertuzzo and, G. Grilli di Cortona, 1705.06325]

Motivating Scenario III: Asymmetric Dark Matter
The (mirror) baryon number stabilizes the dark matter
[D. E. Kaplan, M. Luty and K. M. Zurek, 0901.4117]

The large elastic Xsec allowed between dark matter particles may help solve the so called small scale crisis in cosmology.
[X. Chu, C. Garcia-Cely, H. Murayama, 1901.00075] [J. Terning, C. Verhaaren, K. Zora, 1902.08211]
Many recent efforts/proposals to search for LLPs e.g. [J. Alimena et al, 2203.05502] [J. L. Feng et al, 2203.05090]

One of the perhaps most interesting and challenging scenario: Emerging/semivisible jets made of many dark hadrons. [P. Schwaller, D. Stolarski and A. Weiler, 1502.05409] [T. Cohen, M. Lisanti, H.K. Lou, 1503.00009]
Alternative Tripled Top (TT) Model

The superpotential:

\[ W_{Z_3}' = y_t (Q_A H u_A^c + Q_B H u_B^c + Q_C H u_C^c) + \omega (u'_B u_B^c + u'_C u_C^c) + M (Q_B Q_B'^c + Q_C Q_C'^c) \]

\textbf{A, B & C: 3 sectors charged under different SU(3),}

The soft breaking term:

\[ V_s = \tilde{m}^2 \left( |\tilde{Q}_A|^2 + |\tilde{u}_A^c|^2 \right) - \tilde{m}^2 \left( |\tilde{u}_B^c|^2 + |\tilde{u}_C^c|^2 \right) . \]

A Folded SUSY-like spectrum realized in 4D

For details of the original model, see [H-C. Cheng, LL, E. Salvioni and C. Verhaaren 1803.03561]

1803.03651 1905.03772 20xy.ijklm
Alternate Tripled Top (TT) Model & Accidental SUSY

\[ W'_{Z_3} = y_t (Q_A H u_A^c + Q_B H u_B^c + Q_C H u_C^c) + \omega (u_B^c u_B^c + u_C^c u_C^c) + M (Q_B Q_B^c + Q_C Q_C^c) \]

\[ V'_s = \tilde{m}^2 (|\tilde{Q}_A|^2 + |\tilde{u}_A|^2) - \tilde{m}^2 (|\tilde{Q}_B|^2 + |\tilde{Q}_C|^2) \]

\[ Q_A, u_A^c \quad \text{SM top sector} \]

\[ Q_{B,C} = \begin{pmatrix} t_{B,C} \\ b_{B,C} \end{pmatrix} \sim 2_{-1/2} \]

\[ u_{B/C}^c \sim 1_0 \]

Either light or heavy
Forms one-flavor dark QCD.
Dark hadrons:
Pseudoscalar, Vector and Scalar

\[ \Delta \equiv M^2 - \tilde{m}^2 \to 0 \quad \omega \to 0 \]

Higgs potential left invariant

1803.03651 1905.03772 20xy.ijklm
One flavor Dark QCD- No Dark Pions

Proper decay lengths of Pseudoscalar, Vector and Scalar

M = 2TeV

Long-lived

Prompt

Dark vector meson picks up an effective mixing parameter, similar to a dark photon in the forward/ intensity frontier searches.

$$\varepsilon_{\text{eff}} \approx \frac{1}{2} \sqrt{\frac{\alpha_Z}{\alpha}} \varepsilon_Z \approx 3.8 \times 10^{-7} \left( \frac{\Lambda}{1\text{GeV}} \right)^{3/2} \left( \frac{m_{\tilde{\gamma}}}{2\text{GeV}} \right)^{1/2} \left( \frac{2\text{TeV}}{M} \right)^2$$

Without flavor symmetry, pseudo scalar width scales as: $Y^4\Lambda^3m_f^2/M^4$, $Y^4\Lambda^5/M^4$ for vector.

Easily and naturally become long-lived

Details of phenomenology: [H-C.Cheng, LL, E.Salvioni and C. Verhaareen 1905.03772]
Indirect/Precision Constraints

\[ M \gtrsim 0.9 \text{ TeV} \ Y^2 \left( \frac{N_d N}{6} \right)^{1/2} \]

From EW oblique parameter \( T < O(10^{-3}) \)

\[ \begin{array}{c}
\text{W} \\
\text{W}
\end{array} \]

\[ M \gtrsim 0.4 \text{ TeV} \left( \frac{N_d \text{Tr}(Y Y^\dagger \tilde{Y} \tilde{Y}^\dagger)}{3 \times 10^{-4}} \right)^{1/2} \]

From Higgs invisible decay \( \text{BR} < 13\% \)

\[ \begin{array}{c}
\text{Y} \\
\psi_L
\end{array} \]

\[ M \gtrsim 0.8 \text{ TeV} \ Y \left( \frac{N_d N}{6} \right)^{1/4} \]

From \( Z \) invisible decay width \( \sim 2 \) MeV

\[ \begin{array}{c}
\text{Z} \\
\bar{Q}_R \\
\bar{Q}_R \\
\bar{Y}
\end{array} \]

\[ M \gtrsim 1.5 \text{ TeV} \ Y \tilde{Y} \]

From electron EDM
if CP is violated maximally
Dark Pion Decays (ALP-Like)

ALP with arbitrary flavor diagonal couplings, a step forward from [D. Aloni, Y. Soreq and M. Williams, 1811.03474],

A.1 \( a \to \gamma \gamma \)
A.2 \( a \to \pi^+ \pi^- \gamma \)
A.3 \( a \to \pi^+ \pi^- \pi^0 \)
A.4 \( a \to 3\pi^0 \)
A.5 \( a \to \pi^0 \pi^0 \eta, \pi^+ \pi^- \)
A.6 \( a \to \pi^0 \pi^0 \eta', \pi^+ \pi^- \)
A.7 \( a \to \eta \eta \pi^0 \)
A.8 \( a \to K^0 \bar{K}^0 \pi^0 \)
A.9 \( a \to K^+ K^- \pi^0 \)
A.10 \( a \to K^+ \bar{K}^0 \pi^-, K^- K^0 \pi \)
A.11 \( a \to \omega \omega, \phi \phi, K^{*+} K^{*-}, K^{*0} \bar{K}^{*0} \)
A.12 \( a \to \pi^+ \pi^- \omega \)

\[ \mathcal{L}_a = \frac{1}{2} (\partial \mu a)^2 - \frac{1}{2} m_a^2 a^2 - \frac{\partial \mu a}{f_a} \sum_f c_f \bar{f} \gamma^\mu \gamma_5 f \]

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Dark Pion Decays (ALP-Like, III)

The dominant mode $\pi^+\pi^-\pi^0$ comes from the $\rho\pi\pi$ coupling.

$$\mathcal{M} = \mathcal{M}_{\text{ChPT}} + \mathcal{M}_{\text{VMD}} + \mathcal{M}_\sigma + \mathcal{M}_{f_0} + \mathcal{M}_{f_2}$$

$$\mathcal{M}_{\text{VMD}} = \frac{\langle a\pi_0 \rangle}{f_a} \left\{ g^2 f_\pi \left[ (2m_{12}^2 + m_{23}^2 - m_a^2 - 3m_\pi^2)BW_\rho (m_{23}^2) ight. ight.$$

$$+ (2m_{12}^2 + m_{13}^2 - m_a^2 - 3m_\pi^2)BW_\rho (m_{13}^2) \right] \mathcal{F}_V (m_a) - \frac{1}{2f_\pi (3m_{12}^2 - m_a^2 - 3m_\pi^2)} \Theta (m_{\eta'} - m_a) \right\},$$

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Higgs Portal Decays

Higgs portal decay follows [M. W. Winkler, 1809.01876]

\[ \mathcal{L}_{\text{eff}} \sim -s_\theta \frac{m_f}{v} \hat{\pi} \bar{f} f \]

\( \pi\pi \) or KK dominate low mass region

\[ m_\phi \text{ [GeV]} \]

Hadronic Exclusives

Perturbative QCD results

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Symmetries of the Dark Pion Model

Depending on forms of $\omega, M, Y, \tilde{Y}$, the symmetry of the model varies. We consider 3 benchmarks:

<table>
<thead>
<tr>
<th>Symmetries possessed</th>
<th>Decay portals</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\tilde{Y} = 0$</td>
<td>$\hat{\pi}_1$</td>
</tr>
<tr>
<td>$\checkmark$</td>
<td>$\times$</td>
</tr>
<tr>
<td>$\times$</td>
<td>$\checkmark$</td>
</tr>
<tr>
<td>$\times$</td>
<td>$\times$</td>
</tr>
</tbody>
</table>

- The U(1) subgroup of the SU(2) isospin is exact if everything is diagonal.
- The CP is conserved in the dark sector if all couplings are real.
- The Higgs portal is suppressed if either $Y$ or $\tilde{Y} = 0$.

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Dark Pion as Long-lived Particles

Lifetime between 1mm to >10m

Easy LLP with strong parameter dependence

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LLP in the Z Portal Dominance

\[ f_a^{(1)} \approx 2.5 \text{ PeV} \sim f_\pi^{-1}(y/M)^{-2} \]

\[ f_\pi = 1 \text{ GeV} \]
\[ y/M = 1.1 \text{ TeV}^{-1} \]

cc, ττ, and bb thresholds

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Dark Chiral perturbation Theory

Dark ChpT describe more complicated interaction patterns and dark isospin breaking. Useful at $E \ll m_Z$

$$U = \exp \left( i \frac{\sigma^a \hat{\pi}^a}{f_{\pi}} \right)$$

$$\mathcal{L}_{\pi}^{(2)} \supset \frac{f_{\pi}^2}{4} \text{Tr} \left[ (D^\mu U)^\dagger D_\mu U \right] + \frac{B_0 f_{\pi}^2}{2} \text{Tr} \left[ U \hat{m}_{\psi'} + \hat{m}_{\psi'} U^\dagger \right]$$

$$\hat{m}_{\psi'} = m_{\psi'} - B h$$

$$D_\mu U = \partial_\mu U - i \frac{g_Z}{2} (AU - U \tilde{A}) Z_\mu$$

Possible to include heavier dark hadrons with some help from lattice

Case Study: Z Portal Dominance

\[-\mathcal{L}_{UV} = \overline{Q}_L Y \psi_R H + \overline{Q}_R \tilde{Y} \psi_L H + \overline{Q}_L M Q_R + \overline{\psi}_L \omega \psi_R + h.c.,\]

Higgs invisible decay width constraints irrelevant

\[
Y = \begin{pmatrix}
y_{11} & y_{12} e^{i\alpha} \\
y_{21} & y_{22}
\end{pmatrix}
\]

For N=2 case, contains a free CP phase

\[
\tan 2\theta_{12} \approx \frac{0.20}{1 + 0.036 \left(\frac{4\pi v}{M}\right)^2} \quad \rightarrow \quad \Gamma_{\tilde{\pi}_2} \approx \sin^2 \theta_{12} \Gamma_{\tilde{\pi}_1}
\]

\[
\Rightarrow \quad \pi_2 \text{ decays via the CP-violating mixing with } \pi_1
\]
Phenomenology @ the EW Scale

Z exotic decays to dark quarks with BR:

$$1.8 \times 10^{-4} \left( \frac{N_d \text{Tr}(YY^+YY^+)}{3} + (Y \rightarrow \tilde{Y}) \right) \left( \frac{1 \text{ TeV}}{M} \right)^4$$

Usually dominates the phenomenology because of large stastics:

> $10^{11}$ Z Bosons @ HL-LHC

Higgs portal only relevant when both $Y$, $\tilde{Y}$ are large

$$\sigma_Z \approx 55 \text{ nb}$$

$$\sigma_h \approx 49 \text{ pb}$$
Example: Dimuon Search @ LHCb

Another benchmark with 1 GeV dark pions

Probing $M > 1$ TeV

Allowed by $Z \rightarrow$ inv
decay

Allowed by $Z$ Invisible decay

Allowed by current FCNC bounds
Further Opportunities @ LHC

ATLAS/CMS benefit from larger luminosities and decay volume.

[CMS: CMS-PAS-EXO-20-014]

LLP oriented triggers? [Y. Gershtein and S. Knapen, 1907.00007, D. Linthrone and D. Stolarski, 2103.08620]

Trigger on dimuon DV

Trigger on emerging jet
TeV Scale Phenomenology @ LHC

Direct production of heavy EW doublets:

\[ \hat{\sigma}(u\bar{d} \rightarrow Q_u\bar{Q}_d) = \frac{N_d}{N_c} \frac{\pi \alpha_W^2}{6\hat{s}} \frac{\hat{s}^2}{(\hat{s} - m_W^2)^2} \left( 1 - \frac{4M^2}{\hat{s}} \right)^{1/2} \left( 1 + \frac{2M^2}{\hat{s}} \right) \]

\implies \text{Diboson + emerging jet signals}

If dark pions are invisible, similar with SUSY electroweakino searches.

Estimated limit: \( M > 1.3 \) TeV @ HL-LHC

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Prospect at Future Colliders

Indirect/Intensity (EWPT), Shifting the T parameter:

\[ \hat{T} \sim \frac{N_d}{16\pi^2} \sum_{i=1}^{N} \frac{v^2}{3M_i^2} \left( y_i^4 + \tilde{y}_i^4 + \frac{1}{2} y_i^2 \tilde{y}_i^2 \right) \]

Need Giga-Z

Direct search in H/Z decays:

(VERY conservative) limits on exotic Z → dark shower decays but with a DIFFERENT model.


[H-C. Cheng, LL,E. Salvioni and C. Verhaaren 1905.03772]
Prospect at Future Colliders (II)

Energy-frontier searches:
- VBF pair production
- s-channel pair production
- Indirect, non-resonance modulations
- ...

Intensity-frontier approach: searching in the beam dump:

Y. Sasaki and D. Ueda, [2009.13790].

K. Asai, S. Iwamoto, Y. Sasaki and D. Ueda, [2105.13768].
Comments on Cosmology

Our vanilla dark pion model is not strongly constrained by astrophysical/cosmological observations.

If isospin is exact, all dark pions are stable.

Need extra mediators to keep the dump the entropy generated.

The DM possibilities are still wide open with non-minimal dark components.

e.g., asymmetric baryonic DM or dark mesino/glueballino (dark R-hadrons) in SUSY UV completions.