Composite Dark Matter

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DM @ LHC @ UC Irvine | 4 April 2017
Dark Mesons in Composite Dark Matter Theories

Graham Kribs
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GK, Martin, Neil, Ostdiek, Tong [in preparation]

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Direct Detection

Billard, Strigari, Figueroa-Feliciano; 1307.5458
Interpretation with a Broad Brush

$m_{\text{DM}} \lesssim \text{few GeV}$
(no nuclear recoil above detection threshold)

\[ \frac{y_{\text{eff}} v}{m_{\text{DM}}} \lesssim 0.1 \]

effective coupling of DM to Higgs must be suppressed

$m_{\text{DM}} \gtrsim \text{TeV}$
(suppression of Higgs coupling by at least

\[ \left( \frac{v}{m_{\text{DM}}} \right)^2 \]
Scales in Direct Detection of WIMPs

Usual story is that DM has renormalizable interactions with SM mediators, e.g.,

\[ \text{DM} \xrightarrow{\text{h}} \text{DM} \]

that are integrated out in the NR effective theory to give, e.g. dimension-6 spin-independent operator

\[ \text{DM} \xrightarrow{\text{Z}} \text{DM} \]

But the only scales in town are

\[ \frac{1}{M_Z^2}, \frac{1}{m_h^2} \]
New scale appears in composite DM theories

Effective interactions of strongly-coupled dark matter with SM mediators/matter is higher dimensional:

\[
\frac{1}{(\Lambda_{\text{dark}})^n}
\]

New scale! (natural)
New scale appears in composite DM theories

Effective interactions of strongly-coupled dark matter with SM mediators/matter is higher dimensional:

$$\frac{1}{(\Lambda_{\text{dark}})^n}$$

New scale! (natural)

e.g.:
- magnetic moment:
  $$\frac{\tilde{\psi} \sigma^{\mu\nu} \psi F_{\mu\nu}}{\Lambda_{\text{dark}}}$$
- charge radius:
  $$\frac{(\tilde{\psi} \psi) v^\mu \partial_\nu F_{\mu\nu}}{(\Lambda_{\text{dark}})^2}$$
- polarizability:
  $$\frac{(\tilde{\psi} \psi) F_{\mu\nu} F^{\mu\nu}}{(\Lambda_{\text{dark}})^3}$$

DM

DM
Stealth Dark Matter

Dark matter is a scalar baryon of a strongly-coupled $SU(N_{\text{dark}})$ confining theory with dark fermions transforming under the electroweak group.

Stealth DM

Stealth DM

e.g.:
magnetic moment:

charge radius:

polarizability:

New scale! (natural)

Naturally “stealthy” with respect to direct detection!
Direct Detection Bounds on Stealth Dark Matter

Elastic scattering through polarizability

\[
\sigma_{\text{nucleon}} = \frac{Z^4}{A^2} \frac{144\pi \alpha^4 \mu_{nB}^2 (M_F^A)^2}{m_B^6 R^2} [c_F^2]
\]

Depends on (Z,A), since it doesn’t have A^2-like (Higgs-like) scaling. For Zenon, we obtain:

Confluence of collider and direct detection bounds, but for reasons completely different than ordinary (elementary) WIMPs.
Focus on “dark” mesons

Dark mesons accompanying dark baryonic DM
Focus on “dark” mesons

Dark mesons accompanying dark baryonic DM

Dark mesons as DM

Quirky mesons (confining hidden valleys)

Bosonic technicolor / induced EWSB

Vector-like confinement
Focus on “dark” mesons

Dark mesons accompanying dark baryonic DM

M-theory

Dark mesons as DM

Quirky mesons (confining hidden valleys)

Bosonic technicolor / induced EWSB

Vector-like confinement
# Model Space

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<tr>
<th>Category</th>
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<tr>
<td>Bosonic TC / induced EWSB</td>
<td>Carone, Simmons; hep-ph/9207273</td>
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<td></td>
<td>Brod, Drobnak, Kagan, Stamou, Zupan; 1407.8188</td>
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<td>Chang, Luty, Salvioni, Tsai; 1411.6023</td>
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<td>Kilic, Okui, Sundrum; 0906.0577</td>
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<td>Kilic, Okui; 1001.4526</td>
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<td>Quirky DM</td>
<td>Kribs, Roy, Terning, Zurek; 0909.2034</td>
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<td>Stealth DM</td>
<td>Appelquist et al (LSD Collaboration); 1402.6656; 1503.04203; 1503.04205</td>
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<td>Bai-Hill Dark Mesons</td>
<td>Bai, Hill; 1005.0008</td>
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<td>Buckley-Neil Dark Mesons</td>
<td>Buckley, Neil; 1209.6054</td>
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<td>SIMP (WZW 3-&gt;2)</td>
<td>Hochberg, Kuflik, Murayama, Volansky, Wacker; 1411.3727</td>
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<td>Hochberg, Kuflik, Murayama; 1512.07917</td>
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<td>Light/heavy chiral DM</td>
<td>Harigaya, Nomura; 1603.03430</td>
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<td></td>
<td>Co, Harigaya, Nomura; 1610.03848</td>
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1) Determined by how the dark fermions transform under SM gauge symmetries:

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<th>$SU(2)_L \times U(1)_Y$</th>
<th>$U(1)_Y$ only</th>
<th>$SU(3)_c \times \cdots$</th>
<th>$U(1)_{\text{dark}}$ only</th>
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<td>chiral</td>
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</table>
Model Space II

2) Determined by dark fermion masses relative to confinement scale

\[ m_q \ll \Lambda_{\text{dark}} \quad \text{Chiral limit} \]

\[ m_q \gg \Lambda_{\text{dark}} \quad \text{Darkonia} \]

\[ \Lambda_{\text{dark}} \]
Model Space II

2) Determined by dark fermion masses relative to confinement scale

\[ m_q \sim \Lambda_{dark} \]

\[ \Lambda_{dark} \gtrsim \text{EWSB} \]

Stealth DM; Bai-Hill & Buckley-Neil DM; Vector-like Confinement; Bosonic TC / induced EWSB
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Stealth DM; Bai-Hill & Buckley-Neil DM; Vector-like Confinement; Bosonic TC / induced EWSB

\[ m_q \gtrsim \text{EWSB} \]

\[ \Lambda_{dark} \]

(True) quirky theories; glueball DM
2) Determined by dark fermion masses relative to confinement scale

\[ m_q \sim \Lambda_{\text{dark}} \]

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Stealth DM; Bai-Hill & Buckley-Neil DM; Vector-like Confinement; Bosonic TC / induced EWSB

\[ m_q \gtrsim \text{EWSB} \]

\[ \Lambda_{\text{dark}} \]

(Truly) quirky theories; glueball DM

\[ m_q \]

\[ \Lambda_{\text{dark}} \sim \mathcal{O}(100 \text{ MeV}) \]

Dark U(1) theories; SIMP DM; Light Chiral DM;
# Model Space III: Fermion content

<table>
<thead>
<tr>
<th>Stealth DM</th>
<th>Vector-like confinement (with SU(2) fermion doublets)</th>
<th>Bosonic technicolor / induced EWSB</th>
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<tr>
<td>$SU(N_{\text{dark}})$</td>
<td>$SU(2)_L \times U(1)_Y$</td>
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<td>$F_1$</td>
<td>$N$</td>
<td>$F_1$</td>
</tr>
<tr>
<td>$F_2$</td>
<td>$\overline{N}$</td>
<td>$F_2$</td>
</tr>
<tr>
<td>$(F_{3u})$</td>
<td>$N$</td>
<td>$(F_{4u})$</td>
</tr>
<tr>
<td>$(F_{3d})$</td>
<td>$(1, +1/2)$</td>
<td>$(F_{4d})$</td>
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</tbody>
</table>

| | Hybrid | Pure vector-like | Pure chiral |
| | | | |
| | | | |
| | | | |

Stealth DM

Vector-like confinement

Bosonic technicolor / induced EWSB
Mesons of Stealth Dark Matter

1) **Unlike** bosonic technicolor / induced EWSB (and QCD!);

\[ \langle F_L F_R \rangle \sim \Lambda_{\text{dark}}^3 \]

does not (hugely) break EW symmetry

2) Like bosonic technicolor, there are Higgs interactions with dark fermions

\[ yF_1 HF_{4d} + yF_1 H^\dagger F_{4u} + yF_2 HF_{3d} + yF_2 H^\dagger F_{3u} + h.c. \]

that lead to (small) EW breaking contributions to dark fermion masses
(and break global symmetries down to $U(1)_{\text{dark baryon}}$

3) **Unlike** bosonic technicolor / induced EWSB & vector-like confinement (and QCD!);
(but like some composite Higgs models)

“Tunable” amount of $SU(2)_L \times U(1)_Y$ in $U(4)_V$

$SU(2)_L \times U(1)_Y$ in $U(4)_A$

(preserved vector part of global symmetry)

(broken axial part of global symmetry)
Connecting dark theories together

The “dials” are:

**vector-like masses**

\[ M_{12} \]

\[ M_{34} \]

**Yukawa couplings**

\[ M^d \]

\[ M^u \]

With mass matrices

\[ M^u = \begin{pmatrix} M_{12} & y_{14}^u v / \sqrt{2} \\ y_{23}^u v / \sqrt{2} & M_{34}^u \end{pmatrix} \]

\[ M^d = - \begin{pmatrix} M_{12} & y_{14}^d v / \sqrt{2} \\ y_{23}^d v / \sqrt{2} & M_{34}^d \end{pmatrix} \]

Lead to masses:

\[ q = \pm 1/2 \]

\[ q = \pm 1/2 \]

\[ M_{1,2} = M \mp \sqrt{\Delta^2 + \frac{y_{14} y_{23} v^2}{2}} \]

\[ \Delta \equiv \left| \frac{M_{12} - M_{34}}{2} \right| \]

\[ M \equiv \frac{M_{12} + M_{34}}{2} \]
Contribution to Axial Current

Convenient to expand around the symmetric matrix limit

\[
\left( \begin{array}{cc}
    M_{12} & y_{14}v/\sqrt{2} \\
y_{23}v/\sqrt{2} & M_{34}
\end{array} \right) = \left( \begin{array}{cc}
    M_{12} & yv/\sqrt{2} \\
yv/\sqrt{2} & M_{34}
\end{array} \right) + \frac{\epsilon_y v}{\sqrt{2}} \left( \begin{array}{cc}
    -1 & 1
\end{array} \right) \quad |\epsilon_y| \ll |y|
\]

Obtain

\[
j_{\text{axial}}^{\mu a} \sim c_{\text{axial}} \bar{\Psi}_1 \gamma^\mu \gamma_5 \Psi_1^{(')}
\]

\[
c_{\text{axial}} = \frac{\epsilon_y yv^2}{2M \sqrt{2\Delta^2 + y^2 v^2}}
\]

Critical for light meson decay!

Correct limits:

\[
c_{\text{axial}} \xrightarrow{M \to \infty} 0 \quad c_{\text{axial}} \xrightarrow{yv \to 0} 0
\]
Dark fermions $\rightarrow$ Dark mesons

Consider the limit

$$y v \ll M_{12}, M_{34} < \Lambda_{\text{dark}}$$

Light mesons can be represented in non-linear representation

$$\Sigma = \exp \left[ i \frac{\pi^a t^a}{f_d} \right]$$

$$\pi^a_d \sim \begin{pmatrix}
\pi^0_{d1} & \sqrt{2} \pi^+_{d1} & K_d \text{'s} \\
\sqrt{2} \pi^-_{d1} & -\pi^0_{d1} & \\
K_d \text{'s} & \pi^0_{d2} & \sqrt{2} \pi^+_{d2} \\
\sqrt{2} \pi^-_{d2} & -\pi^0_{d2}
\end{pmatrix}$$

That includes one set of light “dark pions” (d1), eight “dark kaons”, another set of heavier “dark mesons” (d2), and an $\eta$ (not shown).
**Dark pion decay**

Like pion decay in QCD where

\[ \langle 0 | j_{\pm, \text{axial}}^\mu | \pi^\pm \rangle = i f_{\pi} p^\mu \]

\[ \pi^\pm \]

\[ \mu^\pm \]

\[ \nu_\mu \]

\[ \propto y_\mu \]

Lightest dark mesons **decay** through

\[ \langle 0 | j_{\text{axial}}^{\mu a} | \pi_d^a \rangle = i f_d p^\mu \]

\[ \pi_d^\pm \]

\[ \tau^\pm, t(\bar{t}), W^\pm \]

\[ \propto c_{\text{axial}} y_\tau, c_{\text{axial}} y_t, c_{\text{axial}} \frac{k^\mu}{v} \]

\[ \nu_\tau, b(\bar{b}), h \]

But the much larger \( f_d \)

\[ f_\pi \ll f_d \gtrsim \text{weak scale} \]

so dark mesons decay **much faster** than QCD pions even with \( c_{\text{axial}} \ll 1 \)
$\pi^0_d$ decay through anomaly?

Unlike QCD,

\[
\pi^0_d \quad \rightleftharpoons \quad \gamma \quad \gamma
\]

The decay through the anomaly may or may not occur. The QCD anomaly is proportional to

\[
\text{tr}[\tau_3 Q^2_f] \propto N_c [(2/3)^2 - (-1/3)^2]
\]

For stealth dark matter theories, the “u”-like and “d”-like fermions have equal and opposite charge

\[
\text{tr}[\tau_3 Q^2_f] \propto N_{\text{dark}} [(1/2)^2 - (-1/2)^2] = 0
\]

and so \( \pi^0_d \rightarrow \gamma\gamma \) is model dependent.
Dark pion branching fractions

$\pi_d^{0}$

$\pi_d^{\pm}$

Kribs, Martin, Neil, Ostdiek, Tong (to appear)
Dark ρ’s

There are also a set of vector resonances

\[
\rho_d^a \sim \begin{pmatrix}
\rho_{d1}^0 & \sqrt{2}\rho_{d1}^+ \\
\sqrt{2}\rho_{d1}^- & -\rho_{d1}^0 \\
K_d^{*+}'s & K_d^{*-}'s \\
\rho_{d2}^0 & \sqrt{2}\rho_{d2}^+ \\
\sqrt{2}\rho_{d2}^- & -\rho_{d2}^0
\end{pmatrix}
\]

Meson-meson interactions include

\[
g_{\rho_d\pi_d\pi_d} f^{a b c} (\rho_d^a)_\mu \pi_d^b D^\mu \pi_d^c
\]

As well as kinetic mixing with the EW gauge bosons

\[
\epsilon_B B_{\mu\nu} F_{\rho_d}^{\mu\nu} + \epsilon_W W_{\mu\nu} F_{\rho_d'}^{\mu\nu}
\]

Two types!

U(1)-like (\(\rho_d^0\) only)  \[\rightarrow\]  SU(2)-like \(\rho^{\pm,0}\)
Resonance searches for dark $\rho$’s

Upon diagonalizing the kinetic terms, leads to interactions with SM fermions

$$\epsilon \ g \ f^\dagger \bar{\sigma}^\mu (\rho_d)_\mu f$$

which leads to new resonances, e.g.,

The going rate for on-resonant $\rho$ production and decay

$$\sigma(q\bar{q} \rightarrow \rho_d \rightarrow \ell^+ \ell^-) \sim \frac{1}{m_{\rho_d} \Gamma_{\rho_d}^{\text{tot}} S} \Gamma(\rho_d \rightarrow q\bar{q}) \Gamma(\rho_d \rightarrow \ell^+ \ell^-)$$

critically depends on the total width $\Gamma_{\rho_d}^{\text{tot}}$
Resonance searches for dark ρ’s

Two cases:

\[ \frac{m_{\pi_d}}{m_{\rho_d}} < 0.5 \]

The strong 2-body decay
\[ \rho_d \rightarrow \pi_d \pi_d \]
is open, dominates, and leads to a wide resonance:

\[
\frac{\Gamma(\rho_d \rightarrow \pi_d \pi_d)}{m_{\rho_d}} = \frac{g_{\rho_d \pi_d \pi_d}^2 N_{\pi_d}}{96\pi} \left(1 - \frac{4m_{\pi_d}^2}{m_{\rho_d}^2}\right)^{3/2}
\sim 0.25 \left(1 - \frac{4m_{\pi_d}^2}{m_{\rho_d}^2}\right)^{3/2}
\]

\[ \frac{m_{\pi_d}}{m_{\rho_d}} > 0.5 \]

The strong 2-body decay
\[ \rho_d \rightarrow \pi_d \pi_d \]
is closed. Decays to SM modes dominate.
Resonance searches for dark $\rho$'s

Madgraph($pp \rightarrow \rho \rightarrow \ell^+ \ell^-$)
Dark pion production

Production of charged pions proceeds through Drell-Yan

as well as $\rho_d$ exchange

The couplings are:

$$\epsilon \sim g \frac{\sqrt{N_{\text{dark}}}}{4\pi} \quad g_{\rho_d \pi^+ \pi^-} \sim \frac{4\pi}{\sqrt{N_{\text{dark}}}}$$

If $\frac{m_{\pi_d}}{m_{\rho_d}} < 0.5$, dark pions produced resonantly, providing a clear target of opportunity!
Dark pion production

\[ \sigma(pp \rightarrow \tilde{\pi}\tilde{\pi}), \sqrt{s} = 13 \text{ TeV} \]

Cross sections

Preliminary!

- \( SU(2)_{45} \)
- \( SU(2)_{55} \)
- \( U(1)_{45} \)
- \( U(1)_{55} \)

Kribs, Martin, Neil, Ostdiek, Tong (to appear)
Signals of dark pion production

When \( m_{\pi_d} < (m_t + m_b) \)

One can recast new physics searches involving final state tau’s, e.g. EW gauginos @ ATLAS:

Suggests charged dark pions less than about 150-180 GeV are ruled out.

Kribs, Martin, Neil, Ostdiek, Tong (to appear)
Signals of dark pion production

When \( m_{\pi_d} \gtrsim (m_W + m_h) \)

There are no optimal searches for this type of final state. However, same-sign lepton searches (again, SUSY inspired) may have sensitivity:
Thus far, we have found:

Strong constraints on $pp \rightarrow \rho_d \rightarrow \ell^+\ell^-$ when $\frac{m_{\pi_d}}{m_{\rho_d}} > 0.5$

Weak constraints on $pp \rightarrow \rho_d \rightarrow \pi_d\pi_d$

Kribs, Martin, Neil, Ostdiek, Tong (to appear)
Gaps in Searches?

Optimal searches do not exist. In some cases, sensitivity (from other searches) not even clear. For example, when

\[(m_t + m_b) < m_{\pi_d} < (m_W + m_h)\]

Smells like charged Higgs pair production, but with a much larger cross section than Drell-Yan. (We’re still considering some recast-able searches…)
Conclusions

• Highly motivated theories beyond the Standard Model involving new strongly-coupled “dark” sectors are ripe for exploration.

• These “dark” sectors can have particles near EWSB scale and are relevant to a wide class of theories:
  – dark baryonic dark matter theories (i.e., Stealth Dark Matter)
  – dark meson dark matter theories (i.e., Buckley-Neil dark SU(2) mesons)
  – models of EWSB (bosonic technicolor / strongly-coupled induced EWSB)

• Specifics in this talk were motivated by Stealth Dark Matter. This theory provides an existence proof of the power of composites to suppress leading interactions with matter, allowing dark matter to be as light as several hundred GeV.

• Outstanding opportunities for high(er) luminosity searches at LHC — digging into the “several hundred GeV” region with searches involving electroweak particles that may well yield amazing discoveries!