COMPOSITE DARK MATTER
AT COLLIDERS

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Accidental Composite Dark Matter

- Postulate a ‘dark’ sector with new strongly-coupled gauge dynamics

- Dark matter candidate is a bound state stable on cosmological scales due to some accidental symmetry

**Analogy:** proton stable due to accidental baryon number
## Types of accidental composite DM candidates

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See for example: Antipin, Redi, Strumia, Vigiani JHEP 1507 (2015) 039  
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Vector-like theories

Dark fermions transform as vector-like representations under both $G_{DC}$ and $G_{DC} \times G_{SM}$

- mass terms allowed by gauge invariance
- dark condensate aligns in a $G_{SM}$-preserving direction
Vector-like theories

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Example #1

\[
\begin{array}{ccc}
| & SU(N_{DC}) & SU(2)_{EW} & U(1)_{Y} \\
L & \Box & 2 & -1/2 \\
N & \Box & 1 & 0 \\
L^c & \bar{\Box} & 2 & +1/2 \\
N^c & \Box & 1 & 0 \\
\end{array}
\]

\[
\mathcal{L} = -\frac{1}{4g_{DC}^2}g_{\mu \nu}^2 + \bar{L}(i\slashed{D} - M_L)L + \bar{N}(i\slashed{D} - M_N)N + y\bar{N}LH + h.c.
\]

Accidental symmetry: dark baryon number

DM candidate (ex for $N_{DC} = 3$): $NNN$ baryon (spin 3/2) = $1_0$ of $G_{SM}$
Vector-like theories

Dark fermions transform as vector-like representations under both $G_{DC}$ and $G_{DC} \times G_{SM}$

- mass terms allowed by gauge invariance
- dark condensate aligns in a $G_{SM}$-preserving direction

Example #2

\[
\begin{array}{ccc}
SU(N_{DC}) & SU(2)_{EW} & U(1)_Y \\
V & \text{adj} & 3 & 0 \\
\end{array}
\]

\[
\mathcal{L} = -\frac{1}{4g_{DC}^2} G_{\mu\nu}^2 + V^\dagger i\bar{\sigma}^\mu D_\mu V - \frac{M_V}{2} (VV + V^\dagger V^\dagger)
\]

Accidental symmetry: dark parity ($V \rightarrow -V$)

DM candidate: (neutral component of) gluequark $Vg = 3_0$ of $G_{SM}$
Chiral theories

Dark fermions transform as chiral representations under $G_{DC} \times G_D \times G_{SM}$

- no mass term allowed by gauge invariance
- representations vector-like under $G_{SM}$: condensate preserves $G_{SM}$
- representations vector-like under the confining dark color group $G_{DC}$: condensate breaks the weak dark subgroup $G_D$
Chiral theories

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Example

\begin{center}
\begin{tabular}{cccccc}
$SU(N_{DC})$ & $U(1)_D$ & $SU(2)_{EW}$ & $U(1)_{3V}$ & $U(1)_V$ \\
$\psi_1$ & $\square$ & +1 & $\square$ & +1 & +1 \\
$\psi_2$ & $\square$ & $-1$ & $\square$ & $-1$ & +1 \\
$\chi_1$ & $\square$ & $-a$ & $\square$ & $-1$ & $-1$ \\
$\chi_2$ & $\square$ & $+a$ & $\square$ & +1 & $-1$ \\
\end{tabular}
\end{center}

Accidental symmetries: $U(1)_{3V} \times U(1)_V$

DM candidates: i) dark pions $\pi^\pm \sim (\psi_1 \chi_2), (\psi_2 \chi_1)$ ii) lightest dark baryon

Free parameters:
- dark dynamical scale: $\Lambda_D$
- dark coupling: $e_D$
- dark charge: $a$
- hypercharge-dark photon mixing: $\varepsilon$
Light quark regime \((m_\psi \ll \Lambda_{DC})\) - for vectorlike and chiral theories

\(\Lambda_{DC}\)

\(\sim\) weak loop

\(m_\pi\)

spin-0, spin-1, baryons

SM charged NGBs

SM neutral NGBs
Light quark regime \((m_\psi \ll \Lambda_{DC})\) - for vectorlike and chiral theories

\[ m_\pi^2 \sim \frac{g^2}{16\pi^2} \Lambda_{DC}^2 + m_\psi \Lambda_{DC} \]

- pair produced via Drell-Yan
  \[ pp \to V \to \pi\pi \quad (V = W, Z, \gamma) \]
- decay through anomalous/1-loop couplings or Yukawa couplings
  \[ \pi \to VV \]
  \[ \pi \to \pi'V / \pi'H \quad (H = W_L, Z_L, h) \]
Light quark regime \((m_\psi \ll \Lambda_{DC})\) - for vectorlike and chiral theories

Dark pions neutral under the SM

\[ m_\pi^2 \sim m_\psi \Lambda_{DC} \]

- singly produced via VBF, in association with a SM vector boson or from decays of heavier NGBs
- decay to \(VV\) through anomalous couplings

SM neutral NGBs

SM charged NGBs

\( \Lambda_{DC} \) - weak loop

spin-0, spin-1, baryons
Light quark regime \( (m_\psi \ll \Lambda_{DC}) \) - for vectorlike and chiral theories

- singly produced via Drell-Yan
- decay mostly to pairs of NGBs if kinematically allowed, decays to SM fermions parametrically suppressed

\[ \Gamma(\rho \to \pi \pi) \sim \frac{g_\rho^2}{8\pi} m_\rho \]
\[ \Gamma(\rho \to f \bar{f}) \sim \frac{1}{8\pi} \frac{g_{SM}^4}{g_\rho^2} m_\rho \]
**Benchmark:** L+N vectorlike model

\[
SU(3)_L \times SU(3)_R \to SU(3)_V
\]

8 NGBs = \(1_0(\eta) \oplus 2_\pm(K) \oplus 3_0(\pi)\)

under \(SU(2)_{EW} \times U(1)_Y\)

\[
\frac{g}{4\pi} \Lambda_{DC} \lesssim m_\pi < \Lambda_{DC}
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• **Benchmark**: L+N vectorlike model

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**Reach on triplets at the LHC**

[ from: Barducci et al. JHEP 1808 (2018) 017 ]
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• Benchmark: chiral model
  [ R.C., Podo, Revello work in progress ]

\[ SU(4)_L \times SU(4)_R \rightarrow SU(4)_V \]

15 NGBs = \(3^\pm, 3^0, 3^{0'}\), [1\(\pm\), 1\(0\)]

\[ 3^\pm, 3^0, 3^{0'} \]

\[ 1^\pm \]

stable

long-lived

\( \gamma_D \)

stapel
• **Benchmark:** chiral model

[R.C., Podo, Revello work in progress]

\[SU(4)_L \times SU(4)_R \rightarrow SU(4)_V\]

15 NGBs = \(3^{\pm}, 3^0, 3^{0'}, 1^{\pm}, 1^0\) eaten by dark photon

stable (DM candidate)

Reach on triplets at LHC and FCC-hh

- Production: \(pp \rightarrow W/Z/\gamma \rightarrow \pi\pi\)
- Decays: \(3^{\pm} \rightarrow 1^{\pm}W (\gamma_D \gamma_D)\)
  \(3^0 \rightarrow W\gamma_D \gamma_D\)
  \(3^{0'} \rightarrow W\gamma_D\)
  \(\gamma_D \rightarrow f\bar{f}\)
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\( \gamma_D \)'s decay outside the detector, final states with 1, 2, 3 leptons + \( \cancel{E_T} \)

Bounds from LHC searches of gauginos in SUSY
• **Benchmark:** chiral model

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- 3\(^\pm\), 3\(^0\), 3\(^{0^*}\) eaten by dark photon
- 1\(^\pm\) stable

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Reach on triplets at LHC and FCC-hh

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  - \(\gamma_D \rightarrow f\bar{f}\)

\[m_3 = 1.5 m_1\]

\[a = 1/2\]

\(\gamma_D\)'s decay outside the detector, final states with 1,2,3 leptons + \(E_T\)

Bounds from LHC searches of gauginos in SUSY

Displaced vertices from \(\gamma_D\) decays
- **Benchmark:** chiral model

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\( \gamma_D \)'s decay outside the detector, final states with 1,2,3 leptons \( + E_T \)

Bounds from LHC searches of gauginos in SUSY

**Graphical Elements:**
- **Displaced vertices from \( \gamma_D \) decays**
- **Bounds from \( Z' \) searches at the LHC**

**LHC 13TeV**

- **MET**
- **Prompt**
- **Displaced**

**Legend:**
- \( m_3 = 1.5 m_1 \)
- \( a = 1/2 \)
- **Benchmark:** chiral model

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  stable (DM candidate)

  \( \gamma_D \) long-lived

  \[ 3^\pm, 3^0, 3^{0'} \]

  \[ 1^\pm \] stable

Reach on triplets at LHC and FCC-hh

- **Production:** \( pp \rightarrow W/Z/\gamma \rightarrow \pi\pi \)
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  - \( 3^\pm \rightarrow 1^\pm W (\gamma_D \gamma_D) \)
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  - \( \gamma_D \rightarrow f\bar{f} \)

Naive extrapolation to FCC-hh with \( L=20 \text{ab}^{-1} \)
Benchmark: chiral model

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Reach on triplets at LHC and FCC-hh

Summary plot for long-lived dark photons

\[ \epsilon = 10^{-10} \quad a = 1/2 \]
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long-lived \(\gamma_D\)

stable \(B\)

Reach on triplets at LHC and FCC-hh

Summary plot for long-lived dark photons

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Heavy quark regime ($m_\psi \gg \Lambda_{DC}$) - for vectorlike theories

- $\sim N_{DC} m_\psi$: baryons
- $\sim 2m_\psi$: mesons
- $\sim m_\psi$: gluequarks
- $\sim 7\Lambda_{DC}$: glueballs
Heavy quark regime \((m_\psi \gg \Lambda_{DC})\) - for vectorlike theories

Glueballs couple to the SM only via loops of heavy fermions

\(\Gamma[\Phi \to gg] \sim \frac{1}{8\pi} \left(\frac{\alpha_S}{4\pi}\right)^2 \frac{\alpha_{DC}^2(M_N)}{\alpha_{DC}^2(\Lambda_{DC})} \left(\frac{y^2}{16\pi^2}\right)^2 \frac{m_\Phi^9}{M_L^2 M_N^2 (m_h^2 - m_\Phi^2)^2}\)
Heavy quark regime \((m_\psi \gg \Lambda_{DC})\) - for vectorlike theories

Glueballs couple to the SM only via loops of heavy fermions

**Ex:** in the L+N model

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\]

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- \(\sim 2m_\psi\) mesons
- \(\sim m_\psi\) gluequarks
- \(\sim 7\Lambda_{DC}\) glueballs

**LHC 13TeV**

\(\Omega_{DM} h^2 > 0.110\)

In blue: isocurves of \(\sigma(pp \to \Phi)\) for \(y=1, M_L/M_N=2\)
Heavy quark regime \((m_\psi \gg \Lambda_{DC})\) - for vectorlike theories

\[
\sim N_{DC} m_\psi \quad \text{baryons}
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\sim 7\Lambda_{DC} \quad \text{glueballs}
\]

Glueballs couple to the SM only via loops of heavy fermions

\[
\text{Ex: in the L+N model}
\]

\[
G^{2}_{\mu\nu} H^\dagger H
\]

\[
\frac{\alpha_{DC}}{4\pi} \frac{y^2}{M_L M_N} G^{2}_{\mu\nu} H^\dagger H
\]

\[
\Gamma[\Phi \rightarrow gg] \sim \frac{1}{8\pi} \left(\frac{\alpha_S}{4\pi}\right)^2 \frac{\alpha_{DC}^2(M_N)}{\alpha_{DC}^2(\Lambda_{DC})} \left(\frac{y^2}{16\pi^2}\right)^2 \frac{m_\Phi}{M_L^2 M_N^2 (m_h^2 - m_\Phi^2)^2}
\]

**Diagram:**

- FCC-hh
- \(\Omega_{DM} h^2 > 0.110\)
- In blue: isocurves of \(\sigma(pp \rightarrow \Phi)\) for \(y=1, M_L/M_N=2\)
Heavy quark regime \( (m_\psi \gg \Lambda_{DC}) \) - for vectorlike theories

Heavy mesons are *perturbative* quarkonia bound states with calculable properties

- Spin-1 mesons are singly produced via Drell-Yan and have a sizeable (~7%) BR into SM leptons

**Ex:** in the \( V = \text{adj} \) model

**Figure 5:**

Left: ATLAS bounds on the cross section for the direct production of a spin-1 QQ resonance decaying into muons and electrons [49].

Right: Estimated reach on glue-quark pair production obtained by recasting the limits of Ref. [50] from disappearing tracks searches at the HL-LHC (red), the HE-LHC (green) and a 100 TeV collider (blue). The solid (dashed) lines assume a 20\% (500\%) uncertainty on the background estimate.

Both dark quarks are produced in free pairs. Because dark quarks are in the adjoint representation of dark color, when they get separated by a distance of \( O(\Lambda_{DC}) \) they hadronize producing color singlets that fly through the detector. On the contrary, dark quarks in the fundamental representation would not be able to escape, leading to quirks/hidden valley phenomenology [2, 52, 53]. The phenomenology of the open production is then identical to the one of an elementary electroweak multiplet except that the cross-section is enhanced by the multiplicity of the dark color adjoint representation, i.e. \( N_{2DC} \approx 1 \) for SU\(^p\)N\(_{DC}\)q.

Such enhancement factor is not present for gluequark pair production near threshold in the light quark regime. In general, an electroweak triplet can be searched for in monojet and monophoton signals or disappearing tracks, the latter being more constraining. We derived the reach of the high-luminosity LHC (HL-LHC), the high-energy LHC (HE-LHC) and the proposed 100 TeV collider by recasting the results of Ref. [50] for the \( V \) model in the heavy quark regime, see the right plot of Fig. 5. We find that the HL-LHC could discover glue-quark triplets up to \( \approx 600 \) GeV while a 100 TeV collider could reach \( \approx 7 \) TeV. Such bounds are typically weaker than the ones from the production of QQ spin-1 resonances decaying to leptons.

5.2 DM Direct Detection

From the point of view of DM direct detection experiments, where the momentum exchanged is less than 100 KeV, the gluequark behaves as an elementary particle with the same electroweak quantum numbers as the constituent quark. The main difference from elementary candidates with same quantum numbers is that the relic abundance is not controlled by the electroweak interaction, leading to a different thermal region.

For a triplet of SU\(^p\)2q the spin-independent cross-section is \( \sigma^{SI} = 1 \times 10^{4} \text{ cm}^2 \), which is below the neutrino floor for masses \( M < 15 \text{ TeV} \). For an SU\(^p\)2q doublet tree-level \( Z \)-exchange cross-section is

\[ \sigma^{SI} = \frac{1}{4} \times 10^{7} \text{ cm}^2 \]

Dilepton searches at the LHC exclude \( m_\psi < 1.0 - 1.8 \) TeV.

Naive exclusion at FCC-hh (20ab\(^{-1}\)): \( m_\psi < 7 - 13 \) TeV.
Heavy quark regime \( (m_\psi \gg \Lambda_{DC}) \) - for vectorlike theories

- Heavy quarks in the adjoint instead hadronize into dark color-singlet gluequarks
  
  \[ \begin{align*}
  q \rightarrow & \quad \psi \rightarrow \chi & \chi \\
  \bar{q} \rightarrow & \quad \psi \rightarrow \chi & \chi
  \end{align*} \]

  - Heavy quarks in the fundamental lead to string formation and exotic (quirk) signatures
  
  \[ m_{\chi^+} - m_{\chi^0} = 160 \text{ MeV} \]
  \[ \chi^+ \text{ long-lived gives disappearing track (} \chi^+ \rightarrow \chi^0 + \pi^+) \]

At \( E \gtrsim 2m_\psi \), one has open production of \( \bar{\psi} \psi \)

Ex: in the \( V = \text{adj} \) model

\[ m_{\chi^+} - m_{\chi^0} = 160 \text{ MeV} \]

\( \chi^+ \) long-lived gives disappearing track (\( \chi^+ \rightarrow \chi^0 + \pi^+ \))
Collider phenomenology of composite DM models very rich and diverse, still to be fully explored
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Conclusions/Outlook

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- DM candidate can easily be a SM singlet but may have charged partners within collider reach

- Classic DM searches like mono-X do not usually give the strongest bounds/reach
Conclusions/Outlook

- Collider phenomenology of composite DM models very rich and diverse, still to be fully explored

- DM candidate can easily be a SM singlet but may have charged partners within collider reach

- Classic DM searches like mono-X do not usually give the strongest bounds/reach

- More theoretical work needed to identify compelling models