Dark matter at the LHC

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gravitational lensing of galaxy SDP.81, observed by the Atacama Large (sub)Millimeter Array (ALMA)
A bit of history

This course is about 13.8 billion years of cosmic evolution:

At early times, the universe was hot and dense. Interactions between particles were frequent and energetic. Matter was in the form of free electrons and atomic nuclei with light bouncing between them. As the primordial plasma cooled, the light elements—hydrogen, helium and lithium—formed. At some point, the energy had dropped enough for the first stable atoms to exist. At that moment, photons started to stream freely. Today, billions of years later, we observe this afterglow of the Big Bang as microwave radiation. This radiation is found to be almost completely uniform, the same temperature (about 2.7 K) in all directions. Crucially, the cosmic microwave background contains small variations in temperature at a level of 1 part in 10,000. Parts of the sky are slightly hotter, parts slightly colder. These fluctuations reflect tiny variations in the primordial density of matter. Over time, and under the influence of gravity, these matter fluctuations grew. Dense regions were getting denser. Eventually, galaxies, stars and planets formed.

- Dark Matter
- Production
- Dark Energy
- Cosmic Microwave Background
- Structure Formation
- Baryons
- Radiation
- Inflation

This picture of the universe—from fractions of a second after the Big Bang until today—is a scientific fact. However, the story isn't without surprises. The majority of the universe today consists of forms of matter and energy that are unlike anything we have ever seen in terrestrial experiments. Dark matter is required to explain the stability of galaxies and the rate of formation of large-scale structures. Dark energy is required to rationalise the striking fact that the expansion of the universe started to accelerate recently (meaning a few billion years ago). What dark matter and dark energy are is still a mystery. Finally, there is growing evidence that the primordial density perturbations originated from microscopic quantum fluctuations, stretched to cosmic sizes during a period of inflationary expansion. The physical origin of inflation is still a topic of active research.
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FIMP, the new WIMP

Preface

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Inflation

Dark Matter Production

Dark Matter

Production

Cosmic Microwave Background

Structure Formation

Big Bang Nucleosynthesis

Cosmic Microwave Background

Present energy density

Fraction of energy density

Log(T/GeV)

Log(t/sec)

Inflation

0.1 TeV

0.1 MeV

0.1 eV

FIMP

0.1

10

0

-10

-20

-30

0.1 MeV

3 min

0.1 eV

380 kyr

13.8 Gyr

0.1

10

0.1 eV

0.1 MeV

0.1 TeV

fraction of energy density

present energy density
Cosmic history of a FIMP

- **Freeze-out into partners: „secluded“**  
  Pospelov et al. 2007

  \[
  \chi \quad \eta \quad f \\ \\ 
  \chi \quad \bar{f}
  \]

  \[
  \chi \quad \eta \\ \\ 
  \chi
  \]

  \[g_f \ll 1\]

- **Co-annihilation**  
  Griest, Seckel 1991

  \[
  \chi \quad \eta \\ \\ 
  \eta
  \]

  \[
  \chi \\ \\ 
  \chi
  \]

  \[
  \frac{m_{\eta} - m_{\chi}}{m_{\chi}} \ll 1
  \]

- **Freeze-in**  
  Hall et al. 2009

  \[
  \eta \quad \chi \\ \\ 
  \chi \quad \chi
  \]

  \[g_{\chi,f} \ll 1\]
Long-lived dark partners

- Freeze-out into partners

\[
\tau_\eta \sim \frac{1}{m_\eta g_f^2}
\]

- Co-annihilation

\[
\tau_\eta \sim \frac{1}{m_\eta} \left( \frac{m_\eta}{m_\eta - m_\chi} \right)^n
\]

- Freeze-in

\[
\tau_\eta \sim \frac{1}{m_\eta g_{\chi,f}^2}
\]
Portals to a dark sector

couple one new particle without touching SM symmetries

**Neutrino portal:** \[ \mathcal{L} = y_N (\bar{L}H) N + h.c. \]

'sterile neutrino'

**Vector portal:** \[ \mathcal{L} = \epsilon F^{\mu\nu} F'^{\mu\nu} \]

'dark photon'

**Higgs portal:** \[ \mathcal{L} = \lambda_S (H^\dagger H) S \]

'dark scalar'

**Axion portal:** \[ \mathcal{L}_{\text{eff}} = \frac{c_{ff}}{2} \frac{\partial^\mu a}{f_a} (\bar{f} \gamma_\mu \gamma_5 f) \]

'ALP'

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Pospelov, Ritz, Voloshin 2007; Georgi, Kaplan, Randall 1986
Long-lived particles at high energies

The decay length scales as $d = \beta \gamma c \tau$.

**FIG. 1:**
- Left: Dark Higgs decay length
- Right: Dark Higgs decay length for various energies

- $E_\phi = 100$ GeV
- $E_\phi = 1$ TeV
- $E_\phi = 6.5$ TeV
- $E_\phi = 10$ TeV

Decay lengths can be very long. Below the muon threshold, the decay mode dominates in the narrow region $2 < m < 5$ GeV, and interpolate between these two for the intermediate $5 < m < 10$ GeV.

Because the decays are both Yukawa-suppressed, for currently viable values of $m$, the dominant decay modes are to pions, kaons, and other hadrons. This is the high-mass range. On the other hand, for $2 < m < 5$ GeV, dark Higgs bosons can also be produced through other processes. For example, they may pass through many LHC infrastructure components and decay within the FASER volume.

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The gray shaded regions are experimentally excluded.

**B. Dark Higgs Production**

The dark Higgs branching fractions are shown in Fig. 1.
Searches for dark partners

FIG. 1: Near-term and future opportunities to search for visibly decaying massive dark photons interacting through the kinetic mixing vector portal displayed in the dark photon mass ($m_{A'}$)–kinetic mixing ($\epsilon$) parameter space. Constraints from past experiments (gray shaded regions) and projected sensitivities from operating experiments and DUNE (colored shaded regions), proposed near-term (pre-2032) experiments based in the U.S. including Dark Matter New Initiatives (DMNI) supported experiments (solid colored lines), proposed near-term (pre-2032) experiments based internationally and having significant U.S. leadership (dashed colored lines), proposed near-term (pre-2032) international projects (dotted colored lines), and proposed future (post 2032) experiments (dotted gray lines) are shown; see also Figure 3 for another version of this plot with all future experiments labeled. Line coloring indicates the key experimental approach used ($e^+e^-$ collider, $pp$ collider, LHCb LLP detector, electron fixed target, proton fixed target, muon decay), highlighting one aspect of the complementarity between different facilities/experiments. Collectively, these experiments are poised to cover large regions of open dark photon and thermal dark matter parameter space.

Batell et al. 2207.06905
Role of the LHC

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expected event rate:

\[ N(\Delta V) = N_0 \frac{\Delta \Omega}{4\pi} \left[ \exp \left( -\frac{r}{d} \right) - \exp \left( -\frac{r + \Delta r}{d} \right) \right] \]
Axion-like particles

\[ \mathcal{L}_{\text{eff}} = -\frac{m_a^2}{2} a^2 + \frac{c_{\gamma f}}{2} \frac{\partial \mu a}{f_a} \left( \bar{f} \gamma_{\mu} \gamma_{5} f \right) + c_{\gamma V} \frac{a}{f_a} V_{\mu \nu} \bar{V}^{\mu \nu} \]

**LHCb, FASER**

Batell, Pospelov, Ritz
0911.4938

**ATLAS, CMS**

Bauer, Neubert, Thamm
1708.00443

d’Enterria et al.
2203.05939

**ALICE**

Esser et al. 2303.17634
Rygaard et al. to appear

Talk by Marvin Schnubel (Tue)
LHCb: ALPs from meson decays

![Graph showing ALPs from meson decays]
ATLAS, CMS: Displaced ALPs from the top

\[ \sqrt{s} = 13 \text{ TeV} \]

- \( pp \to t\bar{t}a, a \to E_\gamma \): Esser et al. 2303.17634
- \( pp \to t\bar{t}, t \to ca \): Carmona et al. 2202.09371
ALICE: ALPs from photon fusion

Also ATLAS, CMS (heavy-ion runs) talk by Davide Zuliani (Tue)
FASER: Ultra-displaced dark photons

mono-photons: Dienes et al. 2301.05252
Lessons for dark matter?

Figure 4

- **secluded**
  - \( \chi \rightarrow a \)
  - \( \chi \rightarrow \chi \)

- **freeze-in**
  - \( f \rightarrow a \)
  - \( f \rightarrow \chi \)

- **freeze-out**
  - \( \chi \rightarrow a \)
  - \( \chi \rightarrow f \)

- **SM**
  - \( a \rightarrow T \)
  - \( a \rightarrow SM \)

- **Mesa** phase diagram:
  - For different phases of the diagram,
  - \( g \approx 10^{-6} \)

Lessons for dark matter?

Chu, Hambye, Tytgat 1112.0493; Bharucha et al. 2209.03932
Lessons for dark matter?

- freeze-in
- freeze-out
- long-lived partners
- excluded
- missing energy
Dark Matter at the LHC

FIMPs?
Dark Matter beyond the LHC

FIMPs?

colliders

big-bang nucleosynthesis

direct detection

???

cosmic microwave background