Nonstandard Dark Matter Signatures at the LHC

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Outline

• Motivation for general nonstandard DM models

• Inelastic dark matter models

• Strongly interacting dark matter models

• Signatures of those models at colliders

• Potential discovery limit at the 7 TeV LHC

• Conclusions
WIMP Mass [GeV/c^2]

WIMP-Nucleon Cross Section [cm^{-2}]

DAMA/Na
CoGeNT
DAMA/I
CDMS
EDELWEISS

XENON100: 1104.2549
explore other approaches to cover more regions

assuming only null results from direct detection
From Roni Harnik’s talk on Sunday:

Buchmueller et al.
Dark matter and collider connection or fighting

from Hitoshi Murayama’s talk on Sunday
Direct Detection

\[ \chi \quad P \quad \chi \quad P \]

Colliders

\[ \chi \quad P \quad \chi \quad P \quad (\overline{P}) \]
In stead of studying neutralinos in SUSY

Model-independent approach to dark matter

\[
\frac{1}{\Lambda^2} \bar{q}q \bar{\chi}\chi
\]

\[
\frac{1}{\Lambda^2} \bar{q}\gamma_5 q \bar{\chi}\gamma_5 \chi
\]

\[
\frac{1}{\Lambda^2} \bar{q}\gamma_\mu q \bar{\chi}\gamma^\mu \chi
\]

\[
\frac{1}{\Lambda^2} \bar{q}\gamma_\mu \gamma_5 q \bar{\chi}\gamma^\mu \gamma_5 \chi
\]

\ldots \ldots \ldots
As a warmup, we can first use the Tevatron existing data to constrain the DM-nucleon interaction strength.

\[
\sigma_{\text{SI}} \propto \begin{cases} 
\bar{d} d \chi \chi \\
\bar{u} u \chi \chi \\
\bar{d} \gamma \mu d \chi \gamma \mu \chi \\
\bar{u} \gamma \mu u \chi \gamma \mu \chi 
\end{cases}
\]

\[
\sum \propto \begin{cases} 
\bar{d} \chi \chi \\
\bar{u} u \chi \chi \\
\bar{d} \gamma \mu d \chi \gamma \mu \chi \\
\bar{u} \gamma \mu u \chi \gamma \mu \chi 
\end{cases}
\]

YB, Fox, Harnik, JHEP, 1012, 048 (2010)


Fox, Harnik, Kopp, Tsai 1103.0240 for monophoton

some caveats for light mediators
For elastic DM-nucleus scattering, the kinetic energy of dark matter is 

$$E_{\text{kin}} = \frac{1}{2}m_\chi v^2 \sim 100 \text{ keV} \quad m_\chi \sim 100 \text{ GeV}$$

$$\sim 1 \text{ keV} \quad m_\chi \sim 1 \text{ GeV}$$

The typical low energy threshold at direct detection experiments is above 10 keV. Direct detection experiments are insensitive to light DM

Colliders do not have this limitation and can explore light DM region
Mack, Beacom, Bertone: 0705.4298
Strongly interacting dark matter (SIMP)

Colliders can probe this range and the signature is different from monojet


Spergel, Steinhardt: PRL 84, 3760 (2000)
An alternative way to explain the current null results at direct detection experiments is to introduce an extra-dimension.

\[ \Delta \equiv m_{\chi_e} - m_{\chi_g} \geq 1 \text{ MeV} > E_{\text{kin}} \]

no signal at direct detection
Inelastic Dark Matter

However, the LHC may produce those two states at the same time and test a general iDM model with a large mass splitting

T. Han, R. Hempfling, hep-ph/9708264
Hall, Moroi, Murayama, hep-ph/9712515
Tucker-Smith, Weiner, hep-ph/0101138

iDM models:

Perform our studies in a model-independent way:

\[
\frac{\bar{u} \gamma_\mu \gamma_5 u \bar{\chi}_e \gamma^\mu \gamma_5 \chi_g}{\Lambda_1^2} \quad \frac{\bar{u} \gamma_5 u \bar{\chi}_e \gamma_5 \chi_g}{\Lambda_2^2} \quad \frac{\bar{u} u \bar{\chi}_e \chi_g}{\Lambda_3^2} \quad \frac{\bar{u} \gamma_\mu u \bar{\chi}_e \gamma^\mu \chi_g}{\Lambda_4^2}
\]

Three parameters: \( \Lambda \quad m_{\chi_e} \quad \Delta \equiv m_{\chi_e} - m_{\chi_g} \)

The discovery limits at the LHC depend on all of them
The ground state is purely stable and is the dark matter particle.

The excited state is not stable and decays into the ground state plus other SM particles.

For the mass splitting below ~ 1 GeV, using chiral Lagrangian

\[
\frac{\bar{u} \gamma_{\mu} \gamma_{5} u}{\Lambda^2} \chi_{e} \gamma_{\mu} \gamma_{5} \chi_{g} \\
\frac{-i}{2} F_{\pi} \partial^{\mu} \pi^{0} \frac{\bar{\chi}_{e} \gamma_{\mu} \gamma_{5} \chi_{g}}{\Lambda^2} \\
\]

\[
i\bar{u} \gamma_{\mu} \gamma_{5} u \rightarrow \frac{1}{2} F_{\pi} \partial^{\mu} \pi^{0} \\
F_{\pi} = 184 \text{ MeV}
\]

\[
\frac{F_{\pi}}{2 \Lambda^2} \frac{m_{\chi_{e}} + m_{\chi_{g}}}{\pi^{0} \bar{\chi}_{e} \gamma_{5} \chi_{g}}
\]

\[
\Gamma_{0}(\chi_{e} \rightarrow \chi_{g} + \pi^{0}) \\
= \frac{F_{\pi}^2}{\Lambda^4} \frac{(\Delta^2 - m_{\pi^{0}}^2)^{3/2}}{8 \pi}
\]
Translation of the operators

\[ \frac{\bar{u} \gamma_\mu \gamma_5 u \bar{X} e \gamma^\mu \gamma_5 X g}{\Lambda_1^2} \]
\[ \frac{\bar{u} \gamma_5 u \bar{X} e \gamma_5 X g}{\Lambda_2^2} \]
\[ \frac{\bar{u} u \bar{X} e X g}{\Lambda_3^2} \]
\[ \frac{\bar{u} \gamma_\mu u \bar{X} e \gamma^\mu X g}{\Lambda_4^2} \]

Decays of the excited state for \( \Delta \lesssim 1 \) GeV

\[ \Gamma_1(\chi_e \to \chi_g + \pi^0) = \frac{F_\pi^2}{\Lambda_1^4} \frac{(\Delta^2 - m_{\pi^0}^2)^{3/2}}{8 \pi} \]
\[ \Gamma_2(\chi_e \to \chi_g + \pi^0) = \frac{\langle \bar{u}u \rangle^2}{F_\pi^2 \Lambda_2^4} \frac{(\Delta^2 - m_{\pi^0}^2)^{3/2}}{8 \pi m_{\chi}^2} \]
\[ \Gamma_3(\chi_e \to \chi_g \pi^+ \pi^-) = 2 \Gamma_3(\chi_e \to \chi_g 2\pi^0) = \frac{\langle \bar{u}u \rangle^2 \Delta^3}{48\pi^3 F_\pi^4 \Lambda_3^4} \]
\[ \Gamma_4(\chi_e \to \chi_g \pi^+ \pi^-) = \frac{\Delta^5}{240\pi^3 \Lambda_4^4} \]
For $\Delta \gtrsim 1$ GeV, the chiral Lagrangian is not suitable anymore, but one can use a simple parton model to estimate the decay widths

$$\Gamma(\chi e \to \chi g u \bar{u}) = \frac{a_i}{\pi^3} \frac{\Delta^5}{\Lambda_i^4}$$

$$a_1 = 1/20, \ a_3 = a_4 = 1/60, \text{ and } a_2 = \Delta^2 / (560 \bar{m}_\chi^2)$$

decay length at rest

It is generic that the excited state decays with a large displaced vertex

fast moving particle lives longer $c\tau = \gamma c\tau_0$
However, the photons are too soft, because their transverse momenta are related to the mass splitting, which is below 10 GeV.

Fortunately, we can use the initial state radiation to boost final state particles.

The boost can also make the excited state live longer due to time dilation.

The signatures could be:

- non-pointing photons
- displaced pions or jets
For a delayed photon: $t_{\text{corr}} > 0$

For a prompt photon: $t_{\text{corr}} = 0$

a similar signature exists in GMSB models: $\tilde{\chi}^0 \rightarrow \gamma \tilde{G}$
$t_{\text{corr}}$ is not a good variable for the iDM model, as opposite to the GMSB model.

SM backgrounds can also have $t_{\text{corr}}$ up to one ns.

non-pointing photons
Pt distributions of the displaced pions

\[ \frac{m_{\chi}}{E_T > 150 \text{ GeV}} \]

\[ p_T(\pi^0) \sim \frac{E_T}{m_{\chi}} \Delta \]

\[ m_{\chi} = 10 \text{ GeV} \]

\[ \Delta = 1.0 \text{ GeV} \]

\[ m_{\chi} = 50 \text{ GeV} \]

\[ \Delta = 2.0 \text{ GeV} \]
Without using displaced information, the hadronic-tau tagging efficiency can provide some estimation of the discovery potential of the IDM.

- Narrow, collimated
- 1 or 3 tracks
- Can define isolation regions with low activity
- The leading track carries significant fraction of tau momentum

Marcin Wolter, Atlas, talk at Cracow Epiphany Conf., January 2010
discovery (or exclusion) potential at the 7 TeV LHC

\[ N_{jets} \leq 2 \quad p_T(j_1) > 110 \text{ GeV} \quad 15 < p_T(j_2) < 30 \text{ GeV} \quad \mathcal{E}_T \geq 150 \text{ GeV} \]

requiring the excited state to decay before HCAL (1.29 m) and using the tau-tag efficiency

\[ \bar{u} \gamma_\mu \gamma_5 u \bar{X}_e \gamma^\mu \gamma_5 X_g \frac{1}{\Lambda^2_1} \]

IDM signature reach at 5 fb^-1

projected monojet reach at 5 fb^-1

current limit from 36 pb^-1 at CMS: 1106.4775
discovery (or exclusion) potential at the 7 TeV LHC for another operator

\[ \bar{u} u \bar{\chi}_e \chi g \]
\[ \frac{\Lambda_2^2}{\Lambda_3^3} \]

Let's come back from the extra-dimension model (IDM)
Strongly interacting dark matter (SIDM)


Spergel, Steinhardt: PRL 84, 3760 (2000)
Strongly interacting dark matter will be stopped mainly in the HCAL and behaves like a fast neutron.

\[ \mathcal{O} = \frac{i g_X g_q \bar{X} \gamma_\mu X \bar{q} \gamma^\mu q}{q^2 - M^2} \]

\[ \lambda_I = \frac{A}{N_A \cdot \rho \cdot \sigma_{\text{inela}}} \]

For iron: \( \lambda_I^n = 16.8 \text{ cm} \)
For Copper: \( \lambda_I^n = 15.2 \text{ cm} \)

\[
\begin{align*}
\text{HCAL: } & \sim 10 \ \lambda_I \\
\text{ECAL: } & \sim 1 \ \lambda_I
\end{align*}
\]
Strongly interacting dark matter will be stopped mainly in the HCAL and behaves like a fast neutron.

\[ \mathcal{O} = \frac{ig\chi gq \tilde{\chi} \gamma_{\mu} \chi \tilde{\gamma}^{\mu} q}{q^2 - M^2} \]

\[ \lambda_I = \frac{A}{N_A \cdot \rho \cdot \sigma^{\text{inel}}} \]

For iron: \( \lambda_I^n = 16.8 \text{ cm} \)
For Copper: \( \lambda_I^n = 15.2 \text{ cm} \)

HCAL: \( \sim 10 \lambda_I \)
ECAL: \( \sim 1 \lambda_I \)

\text{dark matter} \neq \text{missing energy at the LHC}
SIDM signal events $g_\chi g_u = 1$

seems to be difficult to dig out the SIDM signature
The SIDM signature is different from ordinary dijet

- **No tracks:** *trackless jet*

- Less electromagnetic energy
• **No tracks:** *trackless jet*

Koba-Nielsen-Olesen scaling

\[ P(n) = \frac{1}{\langle n \rangle} e^{-n/\langle n \rangle} \]

using the no-track cut, one can reduce the background by \(~ \left( \frac{1}{20} \right)^2\)
• Less electromagnetic energy

\[ EMF = \text{Jet electromagnetic fraction} = \frac{EM}{(EHAD+EM)} \text{ (CMS jets)} \]

using the cut for less EM in jets, we can reduce the backgrounds by another factor of \( \sim 1/100 \)

It is promising to discover SIDM at the LHC
Conclusion

• A lot of non-standard DM scenarios can only be explored at colliders. There could be more interesting scenarios and signatures that we have not thought about

• The generic signatures of iDM at the LHC could be one hard jet + missing energy + displaced hadrons

• The signature of SIDM is trackless jet

• The discovery limits are promising even for the 7 TeV LHC
Thanks