Searching for dark matter at future colliders

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Outline

- Introduction: DM searches and DM collider searches
- Direct searches at e^+e^- colliders
- Indirect searches at e^+e^- colliders
- Mass measurements of DM
- Searches at future pp colliders
DM searches

- We still do not know what DM is
- Neutral, stable, and weakly interacting
- \( \Omega_{DM}h^2 \approx 0.12 \)
  thermal freeze out? \( \sigma v \approx 3 \times 10^{-26} \text{cm}^3/\text{s} \)
  \( \sigma \approx g^4/m^2, \ m < 1.8 \text{TeV} \ (g^2/0.3) \)
- Weakly Interacting Massive Particle!
- Missing energy at colliders
  (transverse missing energy at hadron colliders)
- Complementarity of three detections
Theoretical approaches

Effective field theories

Simplified models

UV models

Mono-X
Direct production, “model-independent”

Multi final states +ME
Cascade decay, “model-dependent”
Other collider signatures and constraints
Possible studies at $e^+e^-$ colliders

- Disadvantage: Low CM energy; Difficult to directly discover heavy new particles

- Advantage: No large QCD background; precise beam energy; polarized beams; Can accurately measure the mass, spin, and other quantum numbers Complementary to hadron colliders

- Search for light DM $\sim$100GeV Search for interactions between the DM and electrons/EW gauge bosons/Higgs

- Probe relevant particles in new physics models (t-channel annihilation mediator, DM in the EW multiplet...) Indirect search through loop effects, e.g. in Higgs measurements, EW precision measurements
Possible studies at $e^+e^-$ colliders

- Precise measurement rather than discovery
  Full missing energy can be obtained
  Accurately measure the mass, spin, and other quantum numbers of DM

- If a missing particle $\chi$ is discovered at colliders, can it make up all the DM component in the Universe?
  Check the thermal relic density of $\chi$ by using measured DM mass and coupling coefficients.
  Probe the DM production mechanism and cosmological effects of DM
  $\Omega_{\chi} h^2 = 0.12$, strong support for the discovery of DM
  $\Omega_{\chi} h^2 < 0.12$, multi-DM particles? Non-thermal production?
  $\Omega_{\chi} h^2 > 0.12$, some other unexpected annihilation channels? Resonant annihilation? co-annihilation?
Results for DM interactions with electron/positron

- Effective Field Theory: heavy mediator can be integrated out leaving a scale $\Lambda$

$$ O_e = \frac{1}{\Lambda^2} \bar{\chi} \Gamma_\chi \chi \bar{e} \Gamma_e e $$

$$ \Gamma_\chi, \Gamma_e \in \{1, \gamma_5, \gamma^\mu, \gamma^\mu \gamma_5, \sigma^{\mu\nu} \} $$

Search for mono-photon signals from initial state radiations

![Graphs showing results for mono-photon signals from initial state radiations.](image)
Gamma-ray line and mono-photon

- Gamma-ray line is a critical evidence of DM annihilation/decay
- ~3-4 $\sigma$ signals reported by some groups but not confirmed by the Fermi-LAT collaboration.
- Search for corresponding mono-photon signals at future $e^+e^-$ colliders

Effective operator

\[
\mathcal{O}_F = \frac{1}{\Lambda^3} \bar{\chi} i \gamma_5 \chi \tilde{F}_{\mu \nu} F^{\mu \nu}
\]

Cut scale for a ~100 GeV DM and a detectable cross section is ~TeV

\[
\langle \sigma_{\text{ann}} n \rangle_{\chi \bar{\chi} \rightarrow 2\gamma} \approx \frac{4 m_{\chi}^4}{\pi \Lambda^6} = 10^{-27} \text{ cm}^3 \text{ s}^{-1} \left( \frac{m_{\chi}}{130 \text{ GeV}} \right)^4 \left( \frac{1272 \text{ GeV}}{\Lambda} \right)^6
\]

Fermi 1305.5597

Yu, Yan, PFY, 1307.5740
Sensitivities

- Consider possible $e^+e^-$ colliders with CM energies of 250, 500, 1000 and 3000 GeV
- $\pm 3\sigma$ sensitivities for mass scale and annihilation cross section
- Require large luminosities
Mono-Z signals

- DM can interact with both the photon and Z boson
- Consider effective operators

\[ \mathcal{O}_{F1} = \frac{1}{\Lambda_1} \bar{\chi} \chi B_{\mu\nu} B^{\mu\nu} + \frac{1}{\Lambda_2} \bar{\chi} \chi W_{\mu\nu}^a W^{a\mu\nu} \]

\[ \supset \bar{\chi} \chi (G_{Z\gamma} Z_{\mu\nu} Z^{\mu\nu} + G_{AZ} A_{\mu\nu} Z^{\mu\nu}) \]

\[ \mathcal{O}_{F2} = \frac{1}{\Lambda_1} \bar{\chi} i\gamma_5 \chi B_{\mu\nu} B^{\mu\nu} + \frac{1}{\Lambda_2} \bar{\chi} i\gamma_5 \chi W_{\mu\nu}^a W^{a\mu\nu} \]

\[ \supset \bar{\chi} i\gamma_5 \chi (G_{Z\gamma} Z_{\mu\nu} Z^{\mu\nu} + G_{AZ} A_{\mu\nu} Z^{\mu\nu}) \]

\[ \mathcal{O}_{FH} = \frac{1}{\Lambda_3} \bar{\chi} \chi (D_\mu H) \dagger D_\mu H \rightarrow \frac{m_Z^2}{2\Lambda^3} \bar{\chi} \chi Z_{\mu} Z^{\mu} \]

- Z boson can also come from initial state radiation

\[ \mathcal{O}_{FP} = \frac{1}{\Lambda^2} \bar{\chi} \gamma_5 \chi \bar{e} \gamma_5 e, \]

\[ \mathcal{O}_{FA} = \frac{1}{\Lambda^2} \bar{\chi} \gamma_\mu \gamma_5 \chi \bar{e} \gamma_\mu \gamma_5 e \]

Yu, Bi, Yan, PFY,
1404.6990
Sensitivities

- 3σ sensitivities for interactions between the DM and gauge bosons/electrons
- Assume: 1000 fb\(^{-1}\) of data; \(\Lambda=\Lambda_1=\Lambda_2\)
- Compare with the limits from Fermi-LAT dwarf galaxy observations
Assume that DM couples to the SM particles through SM mediators

\[ \mathcal{L} = -h J_h, \quad J_h = \frac{1}{\sqrt{2}} \left[ \sum_f y_f \bar{f} f + \bar{\psi}_{\text{DM}} (y_{\text{DM}} + i y_{\text{DM}}^P \gamma_5) \psi_{\text{DM}} + \frac{\lambda_{\text{DM}uv}}{2} s_{\text{DM}}^2 \right] \]

\[ \mathcal{L} = -Z_{\mu} J_{Z}^{\mu}, \quad J_{Z}^{\mu} = \frac{g_2}{\cos \theta_W} \left[ \sum_f [f \gamma_{\mu} (g_V^{f} + \gamma_5 g_A^{f}) f] + \sum_s g_s[s^* (i \partial_{\mu} s) - (i \partial_{\mu} s^*) s] \right] \]

Searches for invisible Higgs/Z decays are useful to probe light DM

See also H. Zhang’s talk on the Higgs exotic decay at CEPC
Indirect searches at colliders

- There would be some exotic particles carrying EW charges in DM models. These particles might affect SM observations via high order effects.
- May be required by the DM relic density, e.g. t-channel mediator for annihilation, coannihilation ....
- Indirect searches for new physics. Depend on detailed models.
- For instance, calculate the loop correction to the $e^+e^-\rightarrow\mu^+\mu^-$ from a leptophilic DM models with a vector-like fermion $F$ (mediator) and a scalar $S$ (DM).
DM embedded in EW multiplets may interact with Higgs
For instance, a singlet-doublet Fermionic DM model

\[ \mathcal{L}_S = iS_i^\dagger \sigma^{\mu \nu} \partial_{\mu} S - \frac{1}{2} (m_S S \bar{S} + \text{h.c.}), \quad \mathcal{L}_D = iD_i^\dagger \bar{\sigma}^{\mu \nu} D_\mu D_\nu^i + iD_2^\dagger \bar{\sigma}^{\mu \nu} D_2^\dagger \bar{\sigma}^{\mu \nu} D_2^\dagger (m_D \varepsilon_{ij} D_1^i D_1^j + \text{h.c.}) \]

\[ \mathcal{L}_{\text{HSD}} = y_1 H_i S D_1^i - y_2 H_i S D_2^i + \text{h.c.} \]

DM could also be embedded in triplet, quadruplet ....

Could affect the Higgs production process at e+e- colliders

DM and other exotic neutral/charged particles may be directly produced at hadron colliders

e.g. D'Eramo, 0705.4493; Cohen et al, 1109.2604
Test from EW precision measurements

- CEPC measurements would improve the precisions of EW parameters
  See Fan, Reece, Wang, 1411.1054
- Can set constraints on DM (new physics) models

Cai, Yu, et al, in progress
Determination of DM mass at $e^+e^-$ colliders

- Depend on the topology of DM production process
- Consider a process $e^+e^- \rightarrow Y + \bar{Y}$ with $Y \rightarrow a(p_a) + N(k_1)$, $\bar{Y} \rightarrow b(p_b) + \bar{N}(k_2)$
  
  An example is the slepton pair production in SUSY models
- Determine the mass of $Y$ through a threshold scan
- Use kinematic variables to determine $(m_N, m_Y)$
  e.g. visible particle energy endpoint, recoil mass, angle of visible particles....

Brau et.al, 1210.0202

Christensen et.al, 1404.6258
A method of DM mass determination

Consider a process \( e^+e^- \rightarrow Y + \bar{Y} \) with \( Y \rightarrow a(p_a) + N(k_1), \ \bar{Y} \rightarrow b(p_b) + \bar{N}(k_2) \)

For the known initial four-momentum and given particle masses, we have 8 Eqs and 8 variables

\[
q^\mu = p_a^\mu + p_b^\mu + k_1^\mu + k_2^\mu, \quad k_1^2 = k_2^2 = m_N^2, \quad (p_a + k_1)^2 = (p_b + k_2)^2 = m_Y^2
\]

This is a solvable problem at the e^e^- collider

For a wrong set of \((m_N,m_Y)\), above Eqs might not have solutions

Scan the trial \(m_N\)-\(m_Y\) plane and find realistic values by solving the Eqs

Xiang, Bi, Yan, PFY, Yu, in progress
A method of DM mass determination

- For every event, obtain a savable point with the largest distance from the origin in the trial $m_Y$-$m_N$ plane. The coordinates are defined as $(m_Y^{\text{edge}}, m_N^{\text{edge}})$
- Extract $(m_Y, m_N)$ from distributions of $(m_Y^{\text{edge}}, m_N^{\text{edge}})$

See also Harland-Lang et al, 1202.0047
A method of DM mass determination

- Include detector effects in the simulation
- Consider the backgrounds from SM $\mu^+\mu^-+\text{MET}$
- Find realistic values of $(m_N, m_Y)$
A method of DM mass determination

- Deviations of determined masses at a CM energy of 250GeV with 200 fb⁻¹ of data
Searching for DM at the SPPC

- Advantage: large energy and luminosity for the DM production
- Disadvantage: large backgrounds
- Ideal for probing light DM and spin-dependent interactions
- If $Q \gg m_{\text{med}}$, EFT limit is not valid; mediator can be directly produced
From EFT to simplified model

- (minimal) simplified models including $Z'$

\[
\mathcal{L}_{\text{FV}} = \sum_q g_q Z'_\mu \bar{q} \gamma^\mu q + g_\chi Z'_\mu \bar{\chi} \gamma^\mu \chi
\]

\[
\mathcal{L}_{\text{FA}} = \sum_q g_q Z'_\mu \bar{q} \gamma^\mu \gamma_5 q + g_\chi Z'_\mu \bar{\chi} \gamma^\mu \gamma_5 \chi
\]

\[
\mathcal{L}_{\text{SV}} = \sum_q g_q Z'_\mu \bar{q} \gamma^\mu q + ig_\chi Z'_\mu [\chi^* \partial^\mu \chi - (\partial^\mu \chi^*) \chi]
\]

- Require $\Gamma_{Z'} < m_{Z'}$

- For simplicity, assume $g_q = g_\chi$

$g_q$ can be limited by di-jet resonance searches.

In the resonance region, $Z'$ width would affect the DM production rate.
Sensitivities of SppC

- Compare with the limits from the direct detection and indirect detection
- Compare with the parameter regions for the correct thermal DM relic density
- Direct detection limits are derived for $g=0.5$
“Sparticle” simplified model

- Consider a Lagrangian similar to a SUSY model

\[ \Delta L = M_1 \tilde{B}\tilde{B} + M_2 \tilde{W}\tilde{W} + \mu \tilde{H}_u \tilde{H}_d + \sqrt{2} \kappa_1 h^\dagger \tilde{W} \tilde{H}_u + \sqrt{2} \kappa_2 h^\dagger \tilde{W} \tilde{H}_d + \frac{\kappa_1'}{\sqrt{2}} h^\dagger \tilde{B} \tilde{H}_u + \frac{\kappa_2'}{\sqrt{2}} h^\dagger \tilde{B} \tilde{H}_d \]

- DM may be a pure electroweak state or a mixture

- Search strategies are also similar to those for the SUSY: mono-jet, soft leptons, disappearing tracks ….

Arkani et. al, 1511.06495

Low, Wang, 1404.0682
Difficult to directly detect DM signals at $e^+e^-$ colliders

Colliders are ideal tools for probing the light DM

$e^+e^-$ colliders are suitable to measure the DM mass

Complementary to direct and indirect detections
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Thank you!