On the CP Properties of Spin-0 Dark Matter - Unseen, yet promising

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Based on

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with V. Keus, S. Moretti, T. Shindou and J. Hernandez-Sanchez

Scalars 2025: Higgs bosons and cosmology - Warsaw, Poland
September 24, 2025

The Standard Model and its shortcomings

- A Higgs boson discovered
- No significant deviation from the SM
- No signs of new physics

But no explanation for

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- Fermion mass hierarchy
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- Dark Matter & ...

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  Solutions:

  1. Beyond SM scenarios with extended scalar sectors, additional gauge sectors or presence of additional symmetries at higher energies.
  2. Precisely look for any missing signals at colliders.

BSMs to the rescue

Solution: Scalar extensions with a discrete symmetries:

- SM + scalar singlet $\Rightarrow$ DM, ~~CPV~~
- 2HDM: SM + scalar doublet
  - Type-I, Type-II, ...: $\phi_1, \ \phi_2 \ \Rightarrow$ CPV, ~~DM~~
  - IDM - I(1+1)HDM: $\phi_1, \ \phi_2 \ \Rightarrow$ DM, ~~CPV~~
- 3HDM: SM + 2 scalar doublets
  - Weinberg model: $\phi_1, \ \phi_2, \ \phi_3 \ \Rightarrow$ CPV, ~~DM~~
  - I(1+2)HDM: $\phi_1, \ \phi_2, \ \phi_3 \ \Rightarrow$ DM, CPV
  - I(2+1)HDM: $\phi_1, \ \phi_2, \ \phi_3 \ \Rightarrow$ CPV, DM

....This slide is borrowd from Venus Keus's presentation in HPNP2023

I(2+1)HDM: Literature on DM phenomenology and CP violation

- "Classification of finite reparametrization symmetry groups in the three-Higgs-doublet model", I. P. Ivanov, E. Vdovin.
- "Three-Higgs-doublet models: symmetries, potentials and Higgs boson masses", Venus Keus, Stephen F. King, Stefano Moretti.
- "CP violating scalar Dark Matter" and "Dark Matter Signals at the LHC from a 3HDM", A. Cordero-Cid, J. Hernandez-Sanchez, V. Keus, S. F. King, S. Moretti, D. Rojas, D. Sokolowska.
- "A smoking gun signature of the 3HDM", A. Dey, V. Keus, S. Moretti, C. Shepherd-Themistocleous

I(2+1)HDM: collider probs of spin-0 Two-component dark matters

- "On the CP Properties of Spin-0 Dark Matter ", A. Dey, Jaime Hernandez-Sanchez, Venus Keus, Stefano Moretti, Tetsuo Shindou.

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CP-conserving I(2+1)HDM

$Z_2 \times Z_2'$ symmetric scaler potential

"On the CP Properties of Spin-0 Dark Matter: JHEO 06 (2025) 206 "

Scalar extensions with a $Z_2 \times Z_2'$ symmetry: SM + 2 scalar doublets

CP-conserving I(2+1)HDM

$$\phi_1, \phi_2, \phi_3$$

$$g_{Z_2} = diag(-1, +1, +1) \qquad g_{Z_2'} = diag(+1, -1, +1)$$

$$VEV = (0, 0, v)$$

The scalar potential with $Z_2 \times Z_2'$ symmetry

$$V_{3HDM} = V_0 + V_{Z_2\times Z_2'}$$

$$V_0 = \sum_i^3 \left[-\mu_i^2(\phi_i^\dagger\phi_i) + \lambda_{ii}(\phi_i^\dagger\phi_i)^2\right] + \sum_{i,j}^3 \left[\lambda_{ij}(\phi_i^\dagger\phi_i)(\phi_j^\dagger\phi_j) + \lambda'_{ij}(\phi_i^\dagger\phi_j)(\phi_j^\dagger\phi_i)\right]$$

$$V_{Z_2\times Z_2'} = \lambda_1(\phi_1^\dagger\phi_2)^2 + \lambda_2(\phi_2^\dagger\phi_3)^2 + \lambda_3(\phi_3^\dagger\phi_1)^2 + h.c.$$

The Z_2 symmetry

$$\phi_1 \to -\phi_1, \quad \phi_2 \to \phi_2, \quad \phi_3 \to \phi_3, \quad \text{SM fields} \to \text{SM fields}$$

The Z_2' symmetry

$$\phi_1 \to \phi_1, \quad \phi_2 \to -\phi_2, \quad \phi_3 \to \phi_3, \quad \text{SM fields} \to \text{SM fields}$$

Parameters of the model

- All parameters of the potential to be real
- "complete-dark" parameters $\lambda_{11}, \lambda_{22}$ (values have been fixed 0.1 in agreement with the theoretical constraints.)
  "dark-conversion" parameters $\lambda_1, \lambda_{12}, \lambda'_{12}$ (values of λ_{12} and λ'_{12} have been fixed in agreement with the theoretical constraints.)
- fixed by the Higgs mass $\mu_3^2 = v^2\lambda_{33} = m_h^2/2$

8 Important parameters

- Higgs-DM couplings and mass splittings $\lambda_2, \lambda_{23}, \lambda'_{23}, \lambda_3, \lambda_{31}, \lambda'_{31}$,
- Mass scale of inert particles μ_1^2 and μ_2^2

The mass eigenstates

The doublet compositions

$$\phi_1 = \begin{pmatrix} \phi_1^+ \\ \frac{H_1 + iA_1}{\sqrt{2}} \end{pmatrix}, \quad \phi_2 = \begin{pmatrix} \phi_2^+ \\ \frac{H_2 + iA_2}{\sqrt{2}} \end{pmatrix}, \quad \phi_3 = \begin{pmatrix} G^+ \\ \frac{v + h + iG^0}{\sqrt{2}} \end{pmatrix}$$

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First family

$$H_1 : m_{H_1}^2 = -\mu_1^2 + \Lambda_3 v^2$$
$$A_1 : m_{A_1}^2 = -\mu_1^2 + \bar{\Lambda}_3 v^2$$
$$H_1^\pm : m_{H_1^\pm}^2 = -\mu_1^2 + \frac{1}{2}\lambda_{31} v^2$$

Second family

$$H_2 : m_{H_2}^2 = -\mu_2^2 + \Lambda_2 v^2$$
$$A_2 : m_{A_2}^2 = -\mu_2^2 + \bar{\Lambda}_2 v^2$$
$$H_2^\pm : m_{H_2^\pm}^2 = -\mu_2^2 + \frac{1}{2}\lambda_{23} v^2$$

lightest particle from each family is DM candidate

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lightest particle from each family is DM candidate

Two component DM

Input parameters and importance

parameter redefinition

$$\Lambda_1 = \frac{1}{2}(\lambda_{12} + \lambda'_{12} + 2\lambda_1), \qquad \Lambda_2 = \frac{1}{2}(\lambda_{23} + \lambda'_{23} + 2\lambda_2),$$
$$\Lambda_3 = \frac{1}{2}(\lambda_{31} + \lambda'_{31} + 2\lambda_3), \qquad \bar{\Lambda}_1 = \frac{1}{2}(\lambda_{12} + \lambda'_{12} - 2\lambda_1),$$
$$\bar{\Lambda}_2 = \frac{1}{2}(\lambda_{23} + \lambda'_{23} - 2\lambda_2), \qquad \bar{\Lambda}_3 = \frac{1}{2}(\lambda_{31} + \lambda'_{31} - 2\lambda_3)$$

- **Input parameters:**

$$m_h^2,\ m_{H_1}^2,\ m_{H_2}^2,\ m_{A_1}^2,\ m_{A_2}^2,\ m_{H_1^\pm}^2,\ m_{H_2^\pm}^2,\ \Lambda_2,\ \Lambda_3,\ \Lambda_1. \tag{1}$$

Higgs couplins with inert scalars

Couplings controls the DM phenomenology and collider searches:

$$\begin{aligned}
g_{hH_1H_1} &= 2\lambda_3 + \lambda_{31} + \lambda'_{31} = 2\Lambda_3\,, \\
g_{hA_1A_1} &= -2\lambda_3 + \lambda_{31} + \lambda'_{31} = 2\Lambda_3 + 2(m^2_{A_1} - m^2_{H_1})/v^2\,, \\
g_{hH_2H_2} &= 2\lambda_2 + \lambda_{23} + \lambda'_{23} = 2\Lambda_2\,, \\
g_{hA_2A_2} &= -2\lambda_2 + \lambda_{23} + \lambda'_{23} = 2\Lambda_2 + 2(m^2_{A_2} - m^2_{H_2})/v^2\,.
\end{aligned}$$

Two component DM at collider

What about DM phenomenology and possible collider searches?

Two component DM at collider

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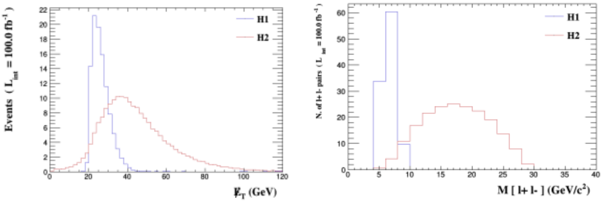
"Complementary collider and astrophysical probes of multi-component Dark Matter", J. Hernandez-Sanchez, V. Keus, S. Moretti, D. Sokolowska.



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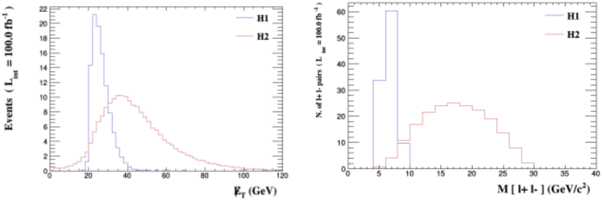

Anything more?

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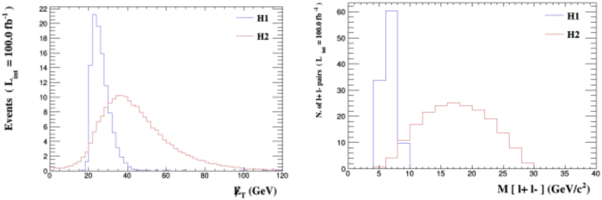

Anything more?

Same or opposite CP partners of Dark matters

CP Properties of DM in two component DM scenario

We looked for two scenarios in which the two components of DM have same CP charge in one case and opposite CP charge in another and there distinguishability in future collider via $2l + \not{E}_T$-channel.

Scenarios

- **Scenario 1**: DM candidates from the two families have same CP.
  DM: H_1 and H_2.
- **Scenario 2**: DM candidates from the two families have opposite CP.
  DM: H_1 and A_2.

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All other characteristics of the DM components are the same

Benchmarks

BP	m_{H_1}	m_{H_2}	$g_{hH_1H_1}$	$g_{hH_2H_2}$	$g_{hA_1A_1}$	$g_{hA_2A_2}$
BP1	80	80	0.192	0.18	0.46	0.37

BP	m_{H_1}	m_{A_2}	$g_{hH_1H_1}$	$g_{hH_2H_2}$	$g_{hA_1A_1}$	$g_{hA_2A_2}$
BP2	80	80	0.192	0.01	0.46	-0.18

Table: For BP1, the cross section is $\sigma(e^+e^- \to \ell^+\ell^- + H_1H_1/H_2H_2) = 2.1$ fb and for the BP2, it is $\sigma(e^+e^- \to \ell^+\ell^- + H_1H_1/A_2A_2) = 1.7$ fb for 1 TeV centre-of-mass energy.

- In each BP, the two DM components have the same mass:

$$m_{H_1}^{BP1} = m_{H_2}^{BP1} = 80 GeV \ , \quad m_{H_1}^{BP2} = m_{A_2}^{BP2} = 80 GeV .$$

- The masses of additional dark scalars in both BPs are the same:

$$m_{A_1}^{BP1} = m_{A_1}^{BP2} = 120 GeV \ , \quad m_{H_{1/2}^{\pm}}^{BP1} = m_{H_{1/2}^{\pm}}^{BP2} = 130 GeV .$$

$$m_{A_2}^{BP1} = m_{H_2}^{BP2} = 110 GeV$$

Diagrams contribute to $\not{E}_T + 2l$ signature at ILC

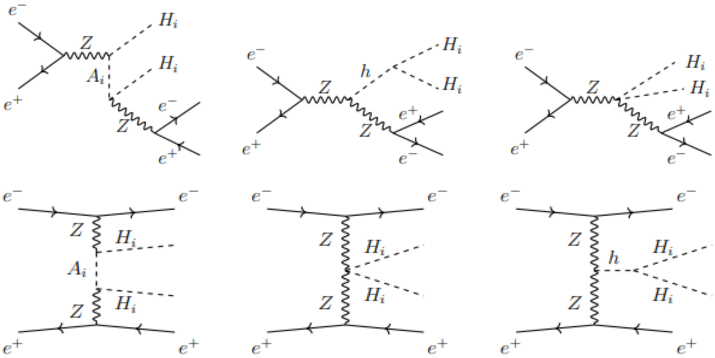

Figure: S- and t-channel diagrams contributing in $\not{E}_T + 2l$ signature.

Distributions of Kinematic variables

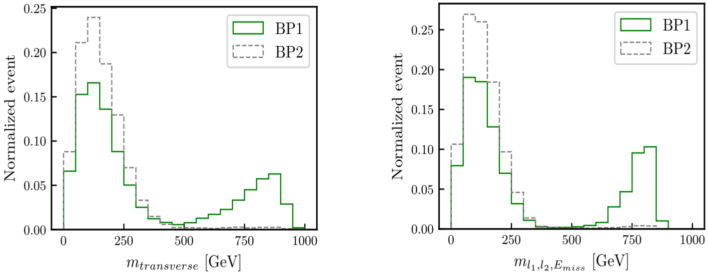

Figure: Normalised distribution of the transverse mass of two lepton and missing energy final state, $m_{transverse}$ (left) and the invariant mass of two leading leptons and missing energy, $m_{\ell_1,\ell_2,E_{miss}}$ (right) at a 1 TeV ILC where e^- and e^+ are 80% and 30% polarised, respectively.

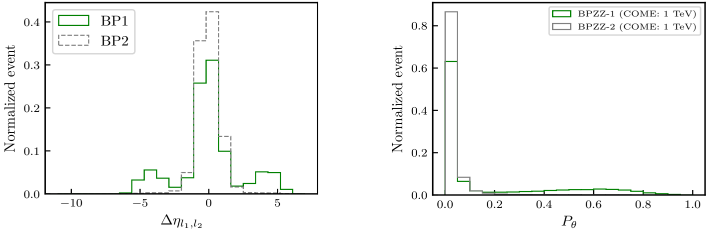

Figure: Normalised distribution of the difference of pseudo-rapidity of two leading leptons $\Delta\eta_{\ell_1,\ell_2}$ on the left and the energy imbalance between missing energy and two leading lepton system P_θ on the right at a 1 TeV ILC where e^- and e^+ are 80% and 30% polarised, respectively.

$$P_\theta = \frac{|E_{miss} - E_{l_1,l_2}|}{E_{miss} + E_{l_1,l_2}}$$

Importance of "t-channel" diagrams

The "t-channel" diagrams

- Recall our 'smoking-gun' signal is found at an ILC through the $e^+e^- \to \ell^+\ell^- + \mathrm{DM\,DM}$ process, where $\ell = e, \mu$.
- The t-channel diagrams would be zero for $e^+e^- \to \mu^+\mu^- + \mathrm{DM\,DM}$ and only s-channel diagrams would contribute.

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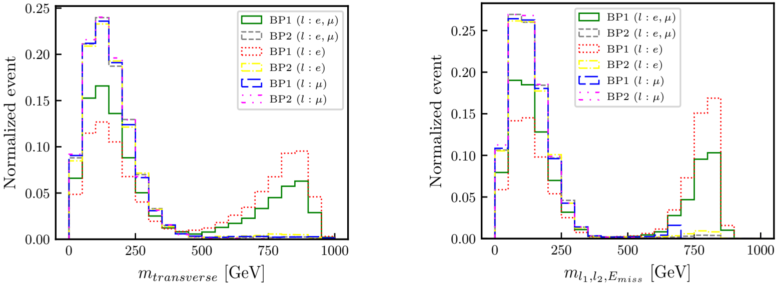
- The t-channel diagrams would be zero for $e^+e^- \to \mu^+\mu^- + \mathrm{DM\,DM}$ and only s-channel diagrams would contribute.
- This observation illustrate that the interference effects is boosted by "t-channel" diagrams and primarily occurring between the t- and s-channel diagrams.

Distributions of Kinematic variables



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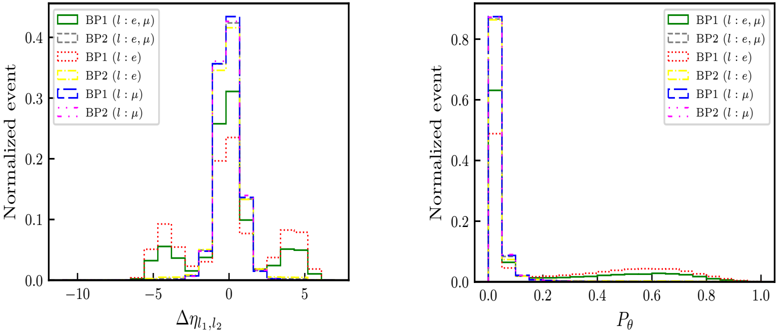
$\not{E}_T + 2l$ signature



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Summary: Inert(2+1)Higgs Doublet Model

- A good DM model with rich phenomenology.
- CP-Conserving I(2+1)HDM
  - SM-like active sector: $H_3 \equiv h^{SM}$
  - The inert sector: $H_{1,2}, A_{1,2}, H^{\pm}_{1,2}$.
  - $Z_2 \times Z_2' - symmetic$: two-component DM.
    - Scalar DM with same or opposite CP partners can be distinguished in future collider.

Thank you for your attaintion