Multi-Component Dark Matter: Identifying at Collider

Purusottam Ghosh

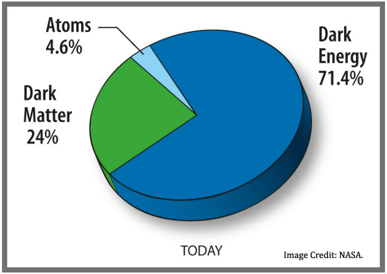
IACS Kolkata

PHOENIX-2023 @ IIT Hyderabad
(18-20 December 2023)

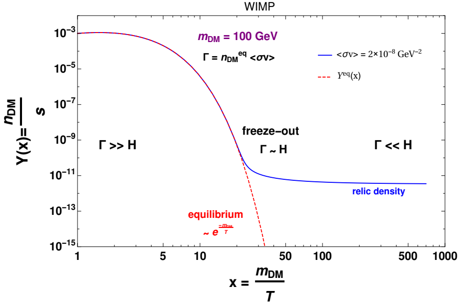
What we know about DM ?

- ✓ Non-luminous and non-baryonic.
- ✓ $\sim 24\%$ of our Universe made of DM.
- ✓ Massive and interact gravitationally.
- ✓ Stable on cosmological time scale.

SM fails to accomodate DM.



Thermal DM : WIMP



- Kinetic Eqlbm. $(T_{\rm DM} = T_{\rm SM})$

  DM SM $\leftrightarrow$ DM SM
- Chemical Eqlbm. $(n^{\rm eq.}_{\rm DM} = n^{\rm eq.}_{\rm SM})$

  DM DM $\leftrightarrow$ SM SM

when $\Gamma << H$:

DM DM $\not\leftrightarrow$ SM SM

DM becomes relic.

- **Why multicomponent DM ?**

- **Why multicomponent DM ?**
  - Null results at direct, indirect and collider searches $\Rightarrow$ the DM sector still remains unknown **including the possibility of having more than one particle**.

- **Why multicomponent DM ?**
  - Null results at direct, indirect and collider searches $\Rightarrow$ the DM sector still remains unknown **including the possibility of having more than one particle**.
  - The visible sector : $\sim 4\%$ of the universe.
    – many fundamental particles (fermions, gauge bosons and Higgs)
    – with different interactions (strong, weak and EM).

- **Why multicomponent DM ?**
  - Null results at direct, indirect and collider searches $\Rightarrow$ the DM sector still remains unknown **including the possibility of having more than one particle**.
  - The visible sector : $\sim 4\%$ of the universe.
    – many fundamental particles (fermions, gauge bosons and Higgs)
    – with different interactions (strong, weak and EM).
  - Too simple to assume only one kind of DM with one specific interaction to contribute $\sim 24\%$ energy density of the universe.

- **Why multicomponent DM ?**
  - Null results at direct, indirect and collider searches $\Rightarrow$ the DM sector still remains unknown **including the possibility of having more than one particle**.
  - The visible sector : $\sim 4\%$ of the universe.
    – many fundamental particles (fermions, gauge bosons and Higgs)
    – with different interactions (strong, weak and EM).
  - Too simple to assume only one kind of DM with one specific interaction to contribute $\sim 24\%$ energy density of the universe.
- **Features of multicomponent DM**

- **Why multicomponent DM ?**
  - Null results at direct, indirect and collider searches ⇒ the DM sector still remains unknown **including the possibility of having more than one particle**.
  - The visible sector : ∼ 4% of the universe.
    – many fundamental particles (fermions, gauge bosons and Higgs)
    – with different interactions (strong, weak and EM).
  - Too simple to assume only one kind of DM with one specific interaction to contribute ∼ 24% energy density of the universe.
- **Features of multicomponent DM**
  - Relic: $\Omega_{\rm DM}h^2 = \Omega_1 h^2 + \Omega_2 h^2 + ... = 0.120 \pm 0.001$ (PLANCK)

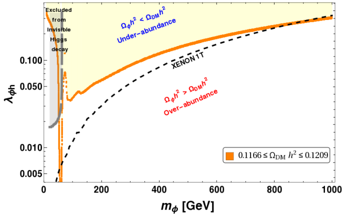
- **Why multicomponent DM ?**
  - Null results at direct, indirect and collider searches $\Rightarrow$ the DM sector still remains unknown **including the possibility of having more than one particle**.
  - The visible sector : $\sim 4\%$ of the universe.
    – many fundamental particles (fermions, gauge bosons and Higgs)
    – with different interactions (strong, weak and EM).
  - Too simple to assume only one kind of DM with one specific interaction to contribute $\sim 24\%$ energy density of the universe.
- **Features of multicomponent DM**
  - Relic: $\Omega_{\rm DM}h^2 = \Omega_1 h^2 + \Omega_2 h^2 + ... = 0.120 \pm 0.001$ (PLANCK)
  - DM Conversion: DM1+ DM1 $\rightarrow$ DM2+ DM2 $\Rightarrow$ leads to modified freezeout $\rightarrow$ Opens up over-abundance region of DM1.

- **Why multicomponent DM ?**
  - Null results at direct, indirect and collider searches $\Rightarrow$ the DM sector still remains unknown **including the possibility of having more than one particle**.
  - The visible sector : $\sim 4\%$ of the universe.
    – many fundamental particles (fermions, gauge bosons and Higgs)
    – with different interactions (strong, weak and EM).
  - Too simple to assume only one kind of DM with one specific interaction to contribute $\sim 24\%$ energy density of the universe.
- **Features of multicomponent DM**
  - Relic: $\Omega_{\rm DM}h^2 = \Omega_1 h^2 + \Omega_2 h^2 + ... = 0.120 \pm 0.001$ (PLANCK)
  - DM Conversion: DM1+ DM1 $\rightarrow$ DM2+ DM2 $\Rightarrow$ leads to modified freezeout $\rightarrow$ Opens up over-abundance region of DM1.
  - DD cross-section: $\sigma_{\rm eff}^{\rm DD}(i) = \big(\Omega_i/\Omega_{\rm DM}\big)\sigma_{\{i-n\}}$.

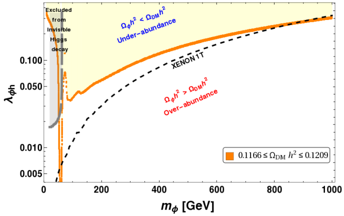
- **Why multicomponent DM ?**
  - Null results at direct, indirect and collider searches $\Rightarrow$ the DM sector still remains unknown **including the possibility of having more than one particle**.
  - The visible sector : $\sim 4\%$ of the universe.
    – many fundamental particles (fermions, gauge bosons and Higgs)
    – with different interactions (strong, weak and EM).
  - Too simple to assume only one kind of DM with one specific interaction to contribute $\sim 24\%$ energy density of the universe.
- **Features of multicomponent DM**
  - Relic: $\Omega_{\rm DM}h^2 = \Omega_1 h^2 + \Omega_2 h^2 + ... = 0.120 \pm 0.001$ (PLANCK)
  - DM Conversion: DM1+ DM1 $\rightarrow$ DM2+ DM2 $\Rightarrow$ leads to modified freezeout $\rightarrow$ Opens up over-abundance region of DM1.
  - DD cross-section: $\sigma^{\rm DD}_{\rm eff}(i) = \big(\Omega_i/\Omega_{\rm DM}\big)\sigma_{\{i-n\}}$.
  - ID cross-section: $\langle\sigma v\rangle^{\rm ID}_{\rm eff}(XY) = \big(\Omega_i/\Omega_{\rm DM}\big)^2\langle\sigma(ii \rightarrow XY)v\rangle$.

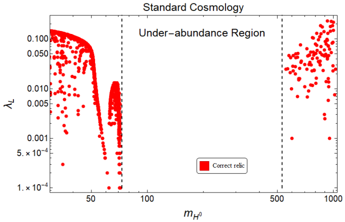
- **Why multicomponent DM ?**
  - Null results at direct, indirect and collider searches $\Rightarrow$ the DM sector still remains unknown **including the possibility of having more than one particle**.
  - The visible sector : $\sim 4\%$ of the universe.
    – many fundamental particles (fermions, gauge bosons and Higgs)
    – with different interactions (strong, weak and EM).
  - Too simple to assume only one kind of DM with one specific interaction to contribute $\sim 24\%$ energy density of the universe.
- **Features of multicomponent DM**
  - Relic: $\Omega_{\rm DM}h^2 = \Omega_1 h^2 + \Omega_2 h^2 + ... = 0.120 \pm 0.001$ (PLANCK)
  - DM Conversion: DM1+ DM1 $\rightarrow$ DM2+ DM2 $\Rightarrow$ leads to modified freezeout $\rightarrow$ Opens up over-abundance region of DM1.
  - DD cross-section: $\sigma^{\rm DD}_{\rm eff}(i) = \left(\Omega_i/\Omega_{\rm DM}\right)\sigma_{\{i-n\}}$.
  - ID cross-section: $\langle\sigma v\rangle^{\rm ID}_{\rm eff}(XY) = \left(\Omega_i/\Omega_{\rm DM}\right)^2\langle\sigma(ii \rightarrow XY)v\rangle$.
  - larger allowed parameter space .. ref. SB, PG.., JHEP 03 (2020) 090

Single Comp. DM: scalar singlet ϕ and inert $\Phi = \begin{pmatrix} H^+ & \frac{H^0 + iA^0}{\sqrt{2}} \end{pmatrix}^T$

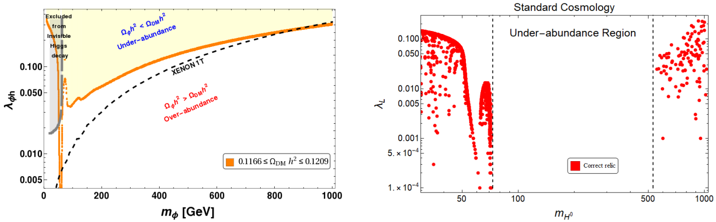


Single Comp. DM: scalar singlet ϕ and inert $\Phi = \begin{pmatrix} H^+ & \frac{H^0 + iA^0}{\sqrt{2}} \end{pmatrix}^T$



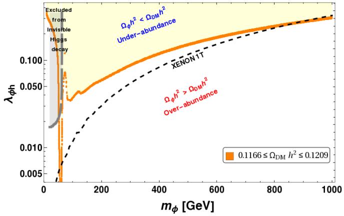


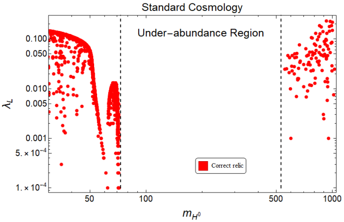
Single Comp. DM: scalar singlet ϕ and inert $\Phi = \begin{pmatrix} H^+ & \frac{H^0 + iA^0}{\sqrt{2}} \end{pmatrix}^T$



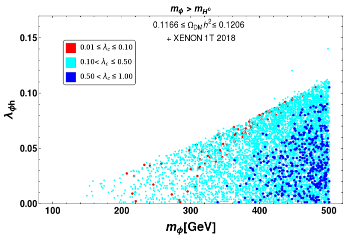
Two Comp. DM: DM1(ϕ)+ DM1(ϕ) $\to$ DM2(Φ)+ DM2(Φ)

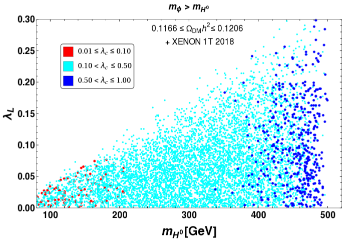
Single Comp. DM: scalar singlet ϕ and inert $\Phi = \begin{pmatrix} H^+ & \frac{H^0 + iA^0}{\sqrt{2}} \end{pmatrix}^T$





Two Comp. DM: DM1(ϕ)+ DM1(ϕ) $\to$ DM2(Φ)+ DM2(Φ)





How one can distinguish the signature of two component DM at collider (ILC) ?

How one can distinguish the signature of two component DM at collider (ILC) ?

Collider Signal of two component Dark Matter:

How one can distinguish the signature of two component DM at collider (ILC) ?

Collider Signal of two component Dark Matter:

1. Dark matter production via cascade decays,
   JHEP 12 (2022) 049 (arXiv: 2202.12097)

How one can distinguish the signature of two component DM at collider (ILC) ?

Collider Signal of two component Dark Matter:

1. Dark matter production via cascade decays,
   JHEP 12 (2022) 049 (arXiv: 2202.12097)
2. **Dark matter production with mono-X**
   Phys. Rev. D 108, L111703 (arXiv:2211.10749)

How one can distinguish the signature of two component DM at collider (ILC) ?

Collider Signal of two component Dark Matter:

1. Dark matter production via cascade decays,
   JHEP 12 (2022) 049 (arXiv: 2202.12097)
2. **Dark matter production with mono-X**
   Phys. Rev. D 108, L111703 (arXiv:2211.10749)

Subhaditya Bhattacharya, **P Ghosh**, Jayita Lahiri and Biswarup Mukhopadhyaya

- Dark sector with $SU(2)_L$ multiplet: $\{X^0(m_{\rm DM}),\ X^{\pm}(m_{\rm DM}+\Delta m),\ .\}$

- Dark sector with $SU(2)_L$ multiplet: $\{X^0(m_{\rm DM}),\ X^\pm(m_{\rm DM}+\Delta m),\ .\}$
- Signal: $\ell^+\ell^- + 0j+$ ME @ ILC

$e^- \ e^+ \to X^+ \ X^-;\ (X^- \to \ \ell^- \ \overline{\nu_\ell} \ X^0),\ (X^+ \to \ell^+ \ \nu_\ell \ X^0)$ (with $\ell = e, \mu$)

- Dark sector with $SU(2)_L$ multiplet: $\{X^0(m_{\rm DM}),\ X^{\pm}(m_{\rm DM}+\Delta m),\ .\}$
- Signal: $\ell^+\ell^- + 0j+$ ME @ ILC

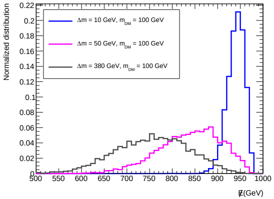
$e^- \; e^+ \to X^+ \; X^-; \; (X^- \to \; \ell^- \; \overline{\nu_\ell} \; X^0), \; (X^+ \to \ell^+ \; \nu_\ell \; X^0)$ (with $\ell = e, \mu$)

The peak of the ME distribution depends on both $m_{\rm DM}$ and Δm:

- Dark sector with $SU(2)_L$ multiplet: $\{X^0(m_{\rm DM}),\ X^{\pm}(m_{\rm DM}+\Delta m),\ .\}$
- Signal: $\ell^+\ell^- + 0j+$ ME @ ILC

$e^- \ e^+ \to X^+ \ X^-;\ (X^- \to \ \ell^- \ \overline{\nu_\ell} \ X^0),\ (X^+ \to \ell^+ \ \nu_\ell \ X^0)$ (with $\ell = e, \mu$)

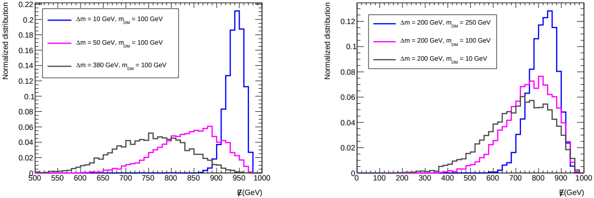
The peak of the ME distribution depends on both $m_{\rm DM}$ and Δm:



- Dark sector with $SU(2)_L$ multiplet: $\{X^0(m_{\rm DM}),\ X^\pm(m_{\rm DM}+\Delta m),\ .\}$
- Signal: $\ell^+\ell^- + 0j+$ ME @ ILC

$e^- \ e^+ \to X^+ \ X^-;\ (X^- \to \ \ell^- \ \overline{\nu_\ell} \ X^0),\ (X^+ \to \ell^+ \ \nu_\ell \ X^0)$ (with $\ell = e, \mu$)

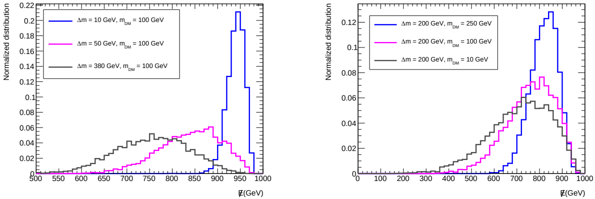
The peak of the ME distribution depends on both $m_{\rm DM}$ and Δm:



- Dark sector with $SU(2)_L$ multiplet: $\{X^0(m_{\rm DM}),\; X^{\pm}(m_{\rm DM} + \Delta m),\; .\}$
- Signal: $\ell^+\ell^- + 0j+$ ME @ ILC

$e^- \; e^+ \to X^+ \; X^-; \; (X^- \to \; \ell^- \; \overline{\nu_\ell} \; X^0), \; (X^+ \to \ell^+ \; \nu_\ell \; X^0)$ (with $\ell = e, \mu$)

The peak of the ME distribution depends on both $m_{\rm DM}$ and Δm:

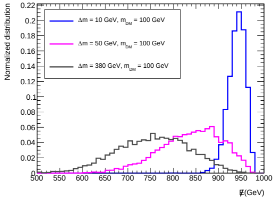


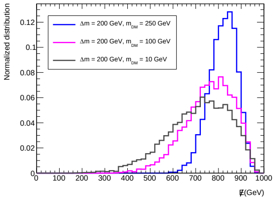
- **Two component DM with** $m_{\rm DM1} \neq m_{\rm DM2}$ and $\Delta m_1 \neq \Delta m_2$

- Dark sector with $SU(2)_L$ multiplet: $\{X^0(m_{\rm DM}),\; X^{\pm}(m_{\rm DM} + \Delta m),\; .\}$
- Signal: $\ell^+\ell^- + 0j +$ ME @ ILC

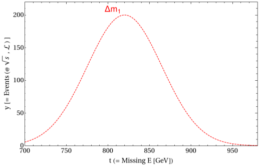
$e^- \; e^+ \to X^+ \; X^-; \; (X^- \to \; \ell^- \; \overline{\nu_\ell} \; X^0), \; (X^+ \to \ell^+ \; \nu_\ell \; X^0)$ (with $\ell = e, \mu$)

The peak of the ME distribution depends on both $m_{\rm DM}$ and Δm:





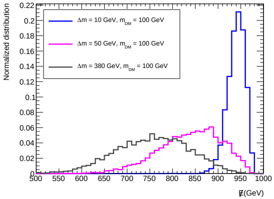
- **Two component DM with** $m_{\rm DM1} \neq m_{\rm DM2}$ and $\Delta m_1 \neq \Delta m_2$

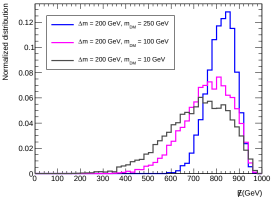


- Dark sector with $SU(2)_L$ multiplet: $\{X^0(m_{\rm DM}),\; X^\pm(m_{\rm DM}+\Delta m),\; .\}$
- Signal: $\ell^+\ell^- + 0j +$ ME @ ILC

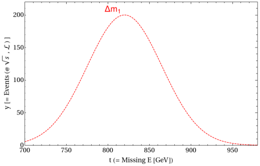
$e^- \; e^+ \to X^+ \; X^-;\; (X^- \to \; \ell^- \; \overline{\nu_\ell} \; X^0),\; (X^+ \to \ell^+ \; \nu_\ell \; X^0)$ (with $\ell = e, \mu$)

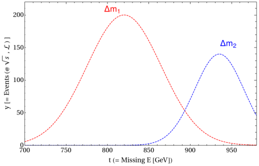
The peak of the ME distribution depends on both $m_{\rm DM}$ and Δm:





- **Two component DM with** $m_{\rm DM1} \neq m_{\rm DM2}$ and $\Delta m_1 \neq \Delta m_2$

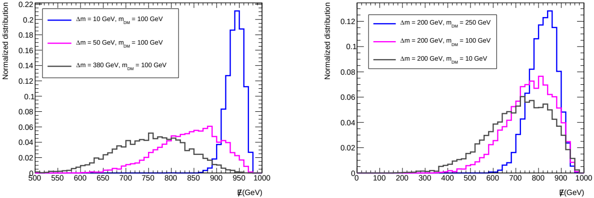




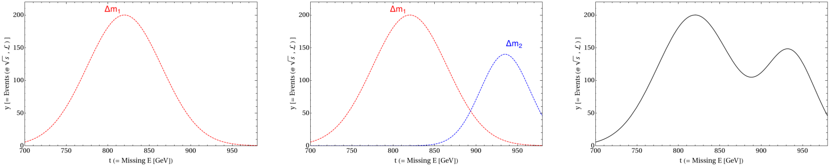
- Dark sector with $SU(2)_L$ multiplet: $\{X^0(m_{\rm DM}),\ X^{\pm}(m_{\rm DM}+\Delta m),\ .\}$
- Signal: $\ell^+\ell^- + 0j+$ ME @ ILC

$e^- \ e^+ \to X^+ \ X^-;\ (X^- \to \ \ell^- \ \overline{\nu_\ell} \ X^0),\ (X^+ \to \ell^+ \ \nu_\ell \ X^0)$ (with $\ell = e, \mu$)

The peak of the ME distribution depends on both $m_{\rm DM}$ and Δm:



- **Two component DM with** $m_{\rm DM1} \neq m_{\rm DM2}$ and $\Delta m_1 \neq \Delta m_2$



A Model with two component DM: $\mathcal{G} = \text{SM} \otimes (\mathcal{Z}_2 \otimes \mathcal{Z}_2')$

A Model with two component DM: $\mathcal{G} = \text{SM} \otimes (\mathcal{Z}_2 \otimes \mathcal{Z}_2')$

- **Scalar DM** (ϕ^0): Inert doublet $\Phi = \begin{pmatrix} \phi^+ & \frac{\phi^0 + iA^0}{\sqrt{2}} \end{pmatrix}^T$; $\Phi \xrightarrow{\mathcal{Z}_2} -\Phi$; with $m_{\phi^0} < m_{\phi^\pm} < m_{A^0}$.

A Model with two component DM: $\mathcal{G} = \text{SM} \otimes (\mathcal{Z}_2 \otimes \mathcal{Z}_2')$

- **Scalar DM** (ϕ^0): Inert doublet $\Phi = \begin{pmatrix} \phi^+ & \frac{\phi^0 + iA^0}{\sqrt{2}} \end{pmatrix}^T$; $\Phi \xrightarrow{\mathcal{Z}_2} -\Phi$;
  with $m_{\phi^0} < m_{\phi^\pm} < m_{A^0}$.
- **Fermion DM** (ψ^0): Lepton doublet $\Psi = \begin{pmatrix} \psi & \psi^- \end{pmatrix}^T$ + Lepton Singlet χ_R ; $(\Psi, \chi) \xrightarrow{\mathcal{Z}_2'} (-\Psi, -\chi)$;
  with $m_{\psi^0} < m_{\psi^\pm} < m_{\psi_2} < m_{\psi_3}$.

A Model with two component DM: $\mathcal{G} = \text{SM} \otimes (\mathcal{Z}_2 \otimes \mathcal{Z}_2')$

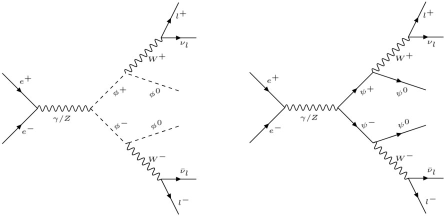
- **Scalar DM** (ϕ^0): Inert doublet $\Phi = \begin{pmatrix} \phi^+ & \frac{\phi^0 + i A^0}{\sqrt{2}} \end{pmatrix}^T$; $\Phi \xrightarrow{\mathcal{Z}_2} -\Phi$;
  with $m_{\phi^0} < m_{\phi^\pm} < m_{A^0}$.
- **Fermion DM** (ψ^0): Lepton doublet $\Psi = \begin{pmatrix} \psi & \psi^- \end{pmatrix}^T$ + Lepton Singlet χ_R ; $(\Psi, \chi) \xrightarrow{\mathcal{Z}_2'} (-\Psi, -\chi)$;
  with $m_{\psi^0} < m_{\psi^\pm} < m_{\psi_2} < m_{\psi_3}$.

Signal and Background: $\ell^+ \ell^- + 0j +$ **ME**

A Model with two component DM: $\mathcal{G} = \text{SM} \otimes (\mathcal{Z}_2 \otimes \mathcal{Z}_2')$

- **Scalar DM** (ϕ^0): Inert doublet $\Phi = \begin{pmatrix} \phi^+ & \frac{\phi^0 + iA^0}{\sqrt{2}} \end{pmatrix}^T$; $\Phi \xrightarrow{\mathcal{Z}_2} -\Phi$;
  with $m_{\phi^0} < m_{\phi^\pm} < m_{A^0}$.
- **Fermion DM** (ψ^0): Lepton doublet $\Psi = \begin{pmatrix} \psi & \psi^- \end{pmatrix}^T$ + Lepton Singlet χ_R ; $(\Psi, \chi) \xrightarrow{\mathcal{Z}_2'} (-\Psi, -\chi)$;
  with $m_{\psi^0} < m_{\psi^\pm} < m_{\psi_2} < m_{\psi_3}$.

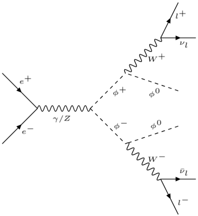
Signal and Background: $\ell^+\ell^- + 0j +$ **ME**

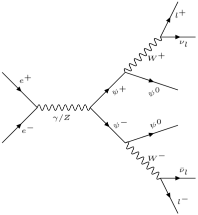


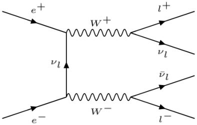
A Model with two component DM: $\mathcal{G} = \text{SM} \otimes (\mathcal{Z}_2 \otimes \mathcal{Z}_2')$

- **Scalar DM** (ϕ^0): Inert doublet $\Phi = \begin{pmatrix} \phi^+ & \frac{\phi^0 + iA^0}{\sqrt{2}} \end{pmatrix}^T$; $\Phi \xrightarrow{\mathcal{Z}_2} -\Phi$; with $m_{\phi^0} < m_{\phi^\pm} < m_{A^0}$.
- **Fermion DM** (ψ^0): Lepton doublet $\Psi = \begin{pmatrix} \psi & \psi^- \end{pmatrix}^T$ + Lepton Singlet χ_R ; $(\Psi, \chi) \xrightarrow{\mathcal{Z}_2'} (-\Psi, -\chi)$; with $m_{\psi^0} < m_{\psi^\pm} < m_{\psi_2} < m_{\psi_3}$.

Signal and Background: $\ell^+\ell^- + 0j +$ ME



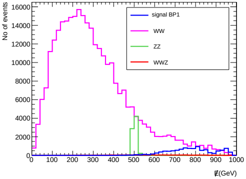




Subhaditya Bhattacharya, **PG**, Jayita Lahiri, Biswarup Mukhopadhyaya JHEP12(2022)049

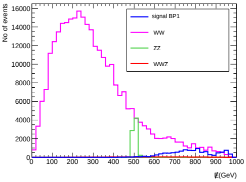
- Beam Polarization+Lepton Energy cut

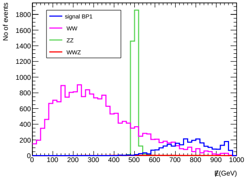
- Beam Polarization+Lepton Energy cut



$P(e^-) = -0.8, P(e^+) = 0.3$

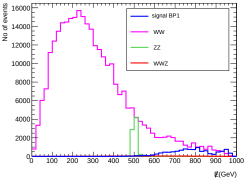
- Beam Polarization+Lepton Energy cut



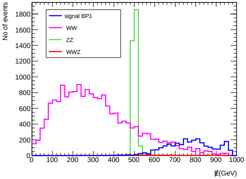


$P(e^-) = -0.8, P(e^+) = 0.3$ $\quad$ $P_{e^-} = +0.8, P_{e^+} = -0.3$

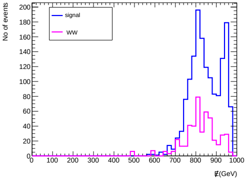
- Beam Polarization+Lepton Energy cut



$P(e^-) = -0.8, P(e^+) = 0.3$

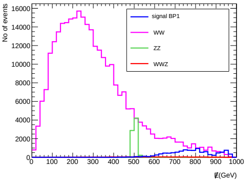


$P_{e^-} = +0.8, P_{e^+} = -0.3$

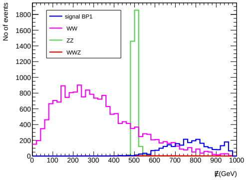


$E(\ell_1) < 150$ GeV

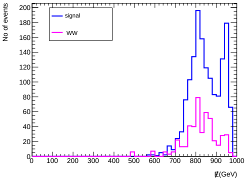
- Beam Polarization+Lepton Energy cut



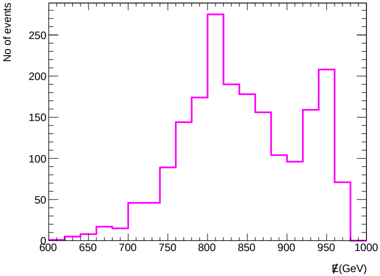
$P(e^-) = -0.8, P(e^+) = 0.3$



$P_{e-} = +0.8, P_{e+} = -0.3$

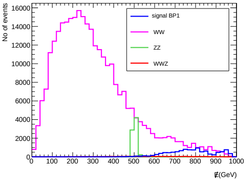


$E(\ell_1) < 150$ GeV

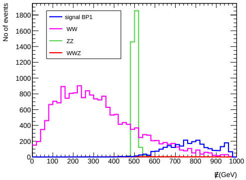


- The signal+background distribution with $S/B = 3$ $\mathcal{S} = 11\sigma$ for BP1.

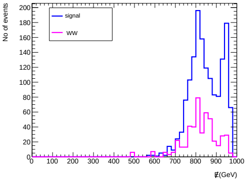
- Beam Polarization+Lepton Energy cut



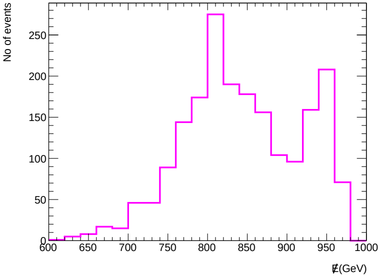
$P(e^-) = -0.8, P(e^+) = 0.3$



$P_{e^-} = +0.8, P_{e^+} = -0.3$

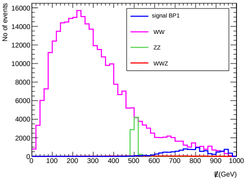


$E(\ell_1) < 150$ GeV

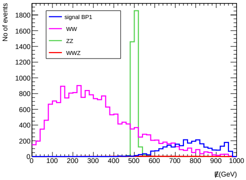


- The signal+background distribution with $S/B = 3$ $\mathcal{S} = 11\sigma$ for BP1.
- The distribution retain the double hump behaviour $\rightarrow$ signature of two component DM.

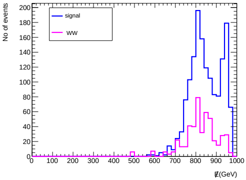
- Beam Polarization+Lepton Energy cut



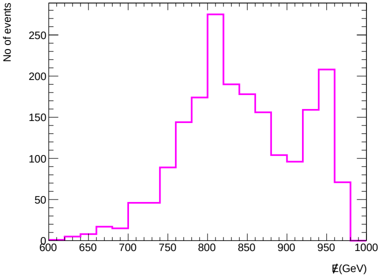
$P(e^-) = -0.8, P(e^+) = 0.3$



$P_{e-} = +0.8, P_{e+} = -0.3$



$E(\ell_1) < 150$ GeV



- The signal+background distribution with $S/B = 3 \;\; \mathcal{S} = 11\sigma$ for BP1.
- The distribution retain the double hump behaviour $\rightarrow$ signature of two component DM.
- The separation of the peaks depends on Δm; while height depnd on production crosssection.

The next question is: how to quantify the distinguishability of the two peaks in a ME distribution? **JHEP12(2022)049**

The next question is: how to quantify the distinguishability of the two peaks in a ME distribution? **JHEP12(2022)049**

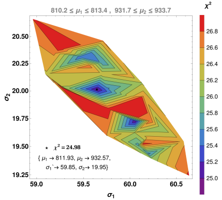
Two peak Gaussian Fitting : $y_H = G(t) = A_1 e^{-\frac{(t-\mu_1)^2}{2\sigma_1^2}} + A_2 e^{-\frac{(t-\mu_2)^2}{2\sigma_2^2}} + \mathcal{B}$

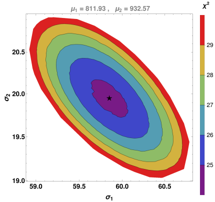
with $\chi^2(\mu_1, \sigma_1; \mu_2, \sigma_2) = \sum_{i=1}^{n} \frac{\left(G(\mu_1,\sigma_1;\mu_2,\sigma_2)[t_H^i] - y_H^i\right)^2}{y_H^i}$.

The next question is: how to quantify the distinguishability of the two peaks in a ME distribution? **JHEP12(2022)049**

Two peak Gaussian Fitting : $y_H = G(t) = A_1 e^{-\frac{(t-\mu_1)^2}{2\sigma_1^2}} + A_2 e^{-\frac{(t-\mu_2)^2}{2\sigma_2^2}} + \mathcal{B}$

with $\chi^2(\mu_1, \sigma_1; \mu_2, \sigma_2) = \sum_{i=1}^{n} \frac{\left(G(\mu_1, \sigma_1; \mu_2, \sigma_2)[t_H^i] - y_H^i\right)^2}{y_H^i}$.

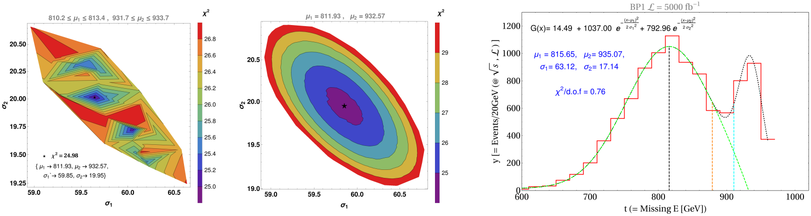




The next question is: how to quantify the distinguishability of the two peaks in a ME distribution? **JHEP12(2022)049**

Two peak Gaussian Fitting : $y_H = G(t) = A_1 e^{-\frac{(t-\mu_1)^2}{2\sigma_1^2}} + A_2 e^{-\frac{(t-\mu_2)^2}{2\sigma_2^2}} + \mathcal{B}$

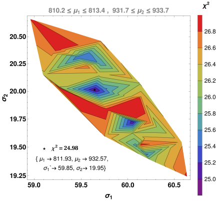
with $\chi^2(\mu_1, \sigma_1; \mu_2, \sigma_2) = \sum_{i=1}^{n} \frac{\left(G(\mu_1,\sigma_1;\mu_2,\sigma_2)[t_H^i] - y_H^i\right)^2}{y_H^i}$.

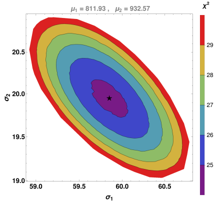


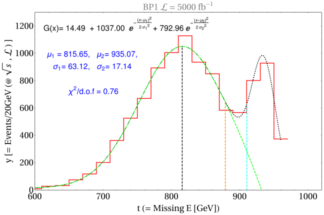
The next question is: how to quantify the distinguishability of the two peaks in a ME distribution? **JHEP12(2022)049**

Two peak Gaussian Fitting : $y_H = G(t) = A_1 e^{-\frac{(t-\mu_1)^2}{2\sigma_1^2}} + A_2 e^{-\frac{(t-\mu_2)^2}{2\sigma_2^2}} + \mathcal{B}$

with $\chi^2(\mu_1, \sigma_1; \mu_2, \sigma_2) = \sum_{i=1}^{n} \frac{\left(G(\mu_1,\sigma_1;\mu_2,\sigma_2)[t_H^i] - y_H^i\right)^2}{y_H^i}$.







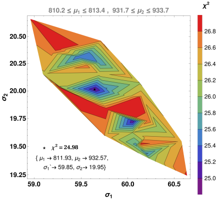
C1 : $\Delta N_1 = \int_t^{t_1} y dt, \quad \Delta N_2 = \int_{t_1}^{t'} y dt \quad R_{C1} = \frac{|\Delta N_2 - \Delta N_1|}{\sqrt{\Delta N_1}} > 2.$

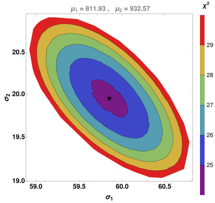
C2 : $R_{C2} = \frac{y(t'') - y'(t'')}{\sqrt{y'(t'')}} > 2;$ C4 : $R_{C4} = \frac{y(t_2) - y(t_{\min})}{\sqrt{y(t_{\min})}} > 2.$

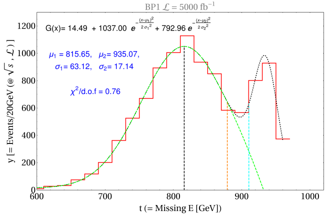
The next question is: how to quantify the distinguishability of the two peaks in a ME distribution? **JHEP12(2022)049**

Two peak Gaussian Fitting : $y_H = G(t) = A_1 e^{-\frac{(t-\mu_1)^2}{2\sigma_1^2}} + A_2 e^{-\frac{(t-\mu_2)^2}{2\sigma_2^2}} + \mathcal{B}$

with $\chi^2(\mu_1, \sigma_1; \mu_2, \sigma_2) = \sum_{i=1}^{n} \frac{\left(G(\mu_1,\sigma_1;\mu_2,\sigma_2)[t_H^i] - y_H^i\right)^2}{y_H^i}$.



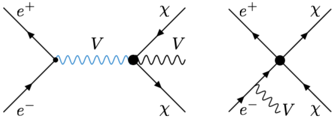




C1 : $\Delta N_1 = \int_t^{t_1} y\,dt, \quad \Delta N_2 = \int_{t_1}^{t'} y\,dt \quad R_{C1} = \frac{|\Delta N_2 - \Delta N_1|}{\sqrt{\Delta N_1}} > 2.$

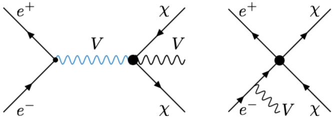
C2 : $R_{C2} = \frac{y(t'') - y'(t'')}{\sqrt{y'(t'')}} > 2;$ C4 : $R_{C4} = \frac{y(t_2) - y(t_{\min})}{\sqrt{y(t_{\min})}} > 2.$

- $R_{C_{1-4}}(\mathcal{L}) > 2\sigma \rightarrow$ There is definitely the presence of second peak.

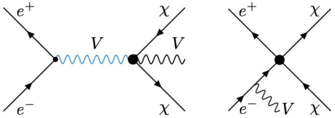


mono-X signal $(X = h, Z, \gamma)$

Two comp. DM with mono-Z signal



mono-X signal $(X = h, Z, \gamma)$

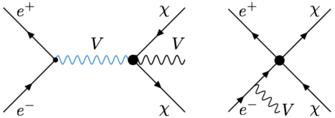


mono-X signal $(X = h, Z, \gamma)$

Two comp. DM with mono-Z signal

DM1: $O_3^s = \frac{c}{\Lambda^2}(B_{\mu\nu}B^{\mu\nu} + W_{\mu\nu}W^{\mu\nu})(\chi^2)$

Two comp. DM with mono-Z signal

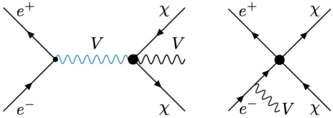


mono-X signal $(X = h, Z, \gamma)$

DM1: $O_3^s = \frac{c}{\Lambda^2}(B_{\mu\nu}B^{\mu\nu} + W_{\mu\nu}W^{\mu\nu})(\chi^2)$

DM2: $O_1^f = \frac{c}{\Lambda^2}(\bar{L}\gamma^\mu L + \bar{\ell}_R\gamma^\mu \ell_R)(\bar{\chi}\gamma_\mu \chi)$

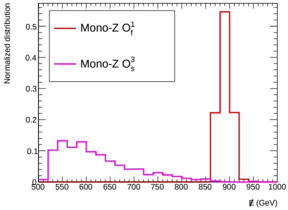
Two comp. DM with mono-Z signal



mono-X signal $(X = h, Z, \gamma)$

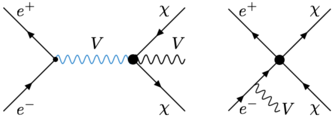
DM1: $O_3^s = \frac{c}{\Lambda^2}(B_{\mu\nu}B^{\mu\nu} + W_{\mu\nu}W^{\mu\nu})(\chi^2)$

DM2: $O_1^f = \frac{c}{\Lambda^2}(\bar{L}\gamma^\mu L + \bar{\ell}_R\gamma^\mu\ell_R)(\bar{\chi}\gamma_\mu\chi)$



Individual DM distribution.

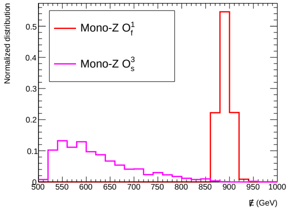
Two comp. DM with mono-Z signal



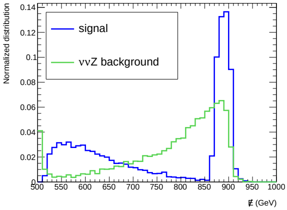
mono-X signal $(X = h, Z, \gamma)$

DM1: $O_3^s = \frac{c}{\Lambda^2}(B_{\mu\nu}B^{\mu\nu} + W_{\mu\nu}W^{\mu\nu})(\chi^2)$

DM2: $O_1^f = \frac{c}{\Lambda^2}(\bar{L}\gamma^\mu L + \bar{\ell}_R\gamma^\mu\ell_R)(\bar{\chi}\gamma_\mu\chi)$

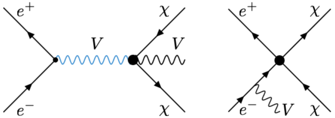


Individual DM distribution.



Two comp. DM with background.

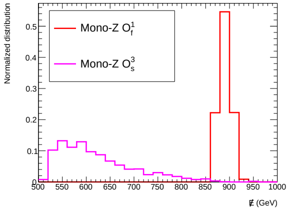
Two comp. DM with mono-Z signal



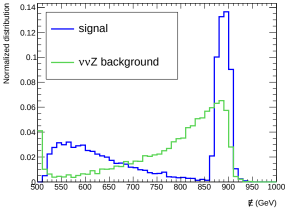
mono-X signal $(X = h, Z, \gamma)$

DM1: $O_3^s = \frac{c}{\Lambda^2}(B_{\mu\nu}B^{\mu\nu} + W_{\mu\nu}W^{\mu\nu})(\chi^2)$

DM2: $O_1^f = \frac{c}{\Lambda^2}(\bar{L}\gamma^\mu L + \bar{\ell}_R\gamma^\mu \ell_R)(\bar{\chi}\gamma_\mu\chi)$

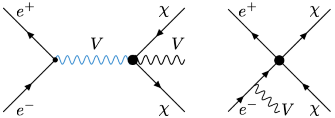


Individual DM distribution.



Two comp. DM with background.

- The large SM background cannot be reduced beyond a certain limit.

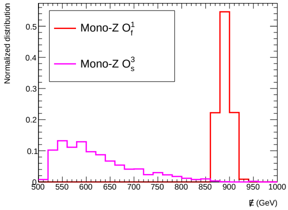


mono-X signal $(X = h, Z, \gamma)$

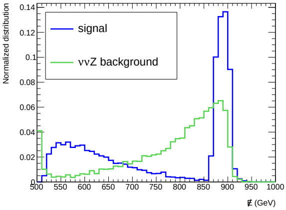
Two comp. DM with mono-Z signal

DM1: $O_3^s = \frac{c}{\Lambda^2}(B_{\mu\nu}B^{\mu\nu} + W_{\mu\nu}W^{\mu\nu})(\chi^2)$

DM2: $O_1^f = \frac{c}{\Lambda^2}(\bar{L}\gamma^\mu L + \bar{\ell}_R\gamma^\mu \ell_R)(\bar{\chi}\gamma_\mu \chi)$



Individual DM distribution.



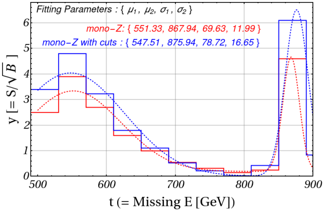
Two comp. DM with background.

- The large SM background cannot be reduced beyond a certain limit.
- Signal+Background distribution can barely show two peak behaviour.

Then the question is: how can we potentially observe a double-hump distribution in a mono-X signal?

Then the question is: how can we potentially observe a double-hump distribution in a mono-X signal?

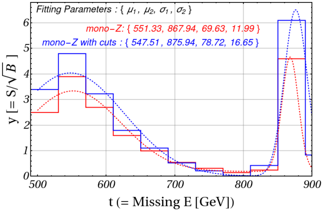
- We propose to look for bin wise signal significance!



Signal significance $(S/\sqrt{B})$

Then the question is: how can we potentially observe a double-hump distribution in a mono-X signal?

- We propose to look for bin wise signal significance!



Signal significance $(S/\sqrt{B})$

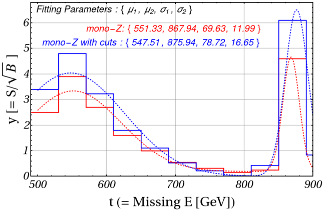
$$R_{C3} = \frac{\int_{t_1^-}^{t_1^+} y dt - \int_{t_2^-}^{t_2^+} y dt}{\int_{t_1^-}^{t_1^+} y dt + \int_{t_2^-}^{t_2^+} y dt},$$

$$R_{C4} = \frac{y(t') - y(t_{\min})}{\sqrt{y(t_{\min})}}$$

$$G(t) \equiv y(t) = A_1\, e^{-\frac{(t-\mu_1)^2}{2\sigma_1^2}} + A_2\, e^{-\frac{(t-\mu_2)^2}{2\sigma_2^2}} + \mathcal{B}$$

Then the question is: how can we potentially observe a double-hump distribution in a mono-X signal?

- We propose to look for bin wise signal significance!



Signal significance $(S/\sqrt{B})$

$$R_{C3} = \frac{\int_{t_1^-}^{t_1^+} y dt - \int_{t_2^-}^{t_2^+} y dt}{\int_{t_1^-}^{t_1^+} y dt + \int_{t_2^-}^{t_2^+} y dt},$$

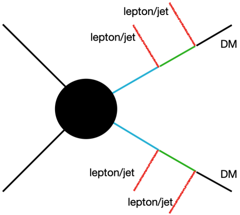
$$R_{C4} = \frac{y(t') - y(t_{\min})}{\sqrt{y(t_{\min})}}$$

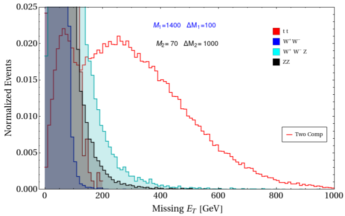
$$G(t) \equiv y(t) = A_1\, e^{-\frac{(t-\mu_1)^2}{2\sigma_1^2}} + A_2\, e^{-\frac{(t-\mu_2)^2}{2\sigma_2^2}} + \mathcal{B}$$

The bin-wise significance comes to the rescue, where one ends up with two-peak only at the presence of the two DM components with $R_{C_{3-4}} > 2\sigma$.

Can we observe two peak distribution at LHC ?

Signal: $\ell^- \ell^+ + 0j + X$





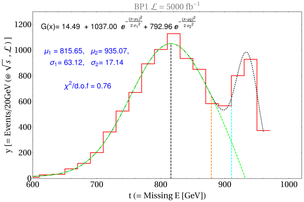
- Two peaks can be observed in the signal.
- The signal encounter a huge QCD background.

Works in Progress ....

The paper **JHEP 04 (2010) 086** by **Partha Konar et al.** studied the signature of multicomponent dark matter at LHC using the M_{T2} topology.

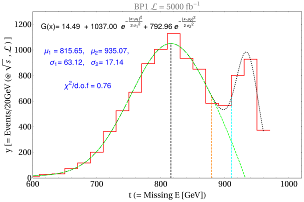
- Double hump distribution is the possible signature of two DMs at ILC.

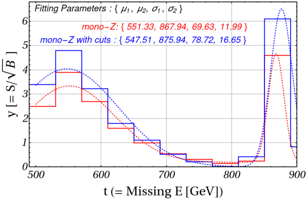
- Double hump distribution is the possible signature of two DMs at ILC.



I. Two DM components producing via cascade decays.

- Double hump distribution is the possible signature of two DMs at ILC.

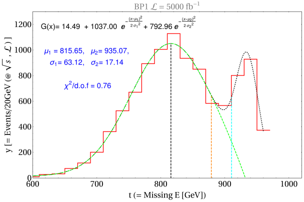


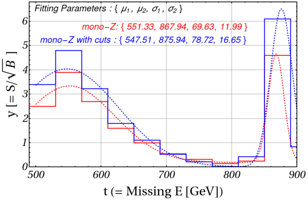


I. Two DM components producing via cascade decays.

II. Two DM components producing with mono-X.

• Double hump distribution is the possible signature of two DMs at ILC.



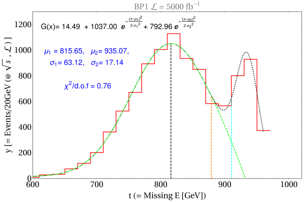


I. Two DM components producing via cascade decays.

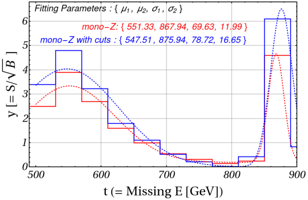
II. Two DM components producing with mono-X.

• Conditions C_{1-4} ($R_{C_{1-4}} > 2\sigma$) can successfully distinguish double peak behaviour in the ME spectrum.

• Double hump distribution is the possible signature of two DMs at ILC.



I. Two DM components producing via cascade decays.

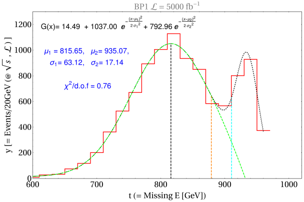


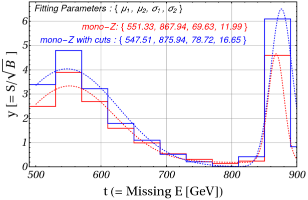
II. Two DM components producing with mono-X.

• Conditions C_{1-4} ($R_{C_{1-4}} > 2\sigma$) can successfully distinguish double peak behaviour in the ME spectrum.

• High luminosity and High energy avoid statistical fluctuations and meets peak separation conditions.

•Double hump distribution is the possible signature of two DMs at ILC.





I. Two DM components producing via cascade decays.

II. Two DM components producing with mono-X.

• Conditions C_{1-4} ($R_{C_{1-4}} > 2\sigma$) can successfully distinguish double peak behaviour in the ME spectrum.

• High luminosity and High energy avoid statistical fluctuations and meets peak separation conditions.

thank you!

Email id **pghoshiitg@gmail.com**

The minimal renormalizable Lagrangian for this model then reads,

$$\mathcal{L} \supset \mathcal{L}^{\rm SDM} + \mathcal{L}^{\rm FDM}. \tag{1}$$

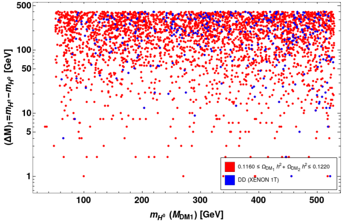
The Lagrangian for the SDM sector, having inert scalar doublet Φ can be written as :

$$\begin{aligned} \mathcal{L}^{\rm SDM} &= \left|\left(\partial^\mu - i g_2 \frac{\sigma^a}{2} W^{a\mu} - i g_1 \frac{Y}{2} B^\mu\right)\Phi\right|^2 - V(\Phi, H)\,; \\ V(\Phi, H) &= \mu_\Phi^2 (\Phi^\dagger\Phi) + \lambda_\Phi (\Phi^\dagger\Phi)^2 + \lambda_1 (H^\dagger H)(\Phi^\dagger\Phi) + \lambda_2 (H^\dagger\Phi)(\Phi^\dagger H) \\ &\quad + \frac{\lambda_3}{2}\left[(H^\dagger\Phi)^2 + h.c.\right] \ . \end{aligned}$$

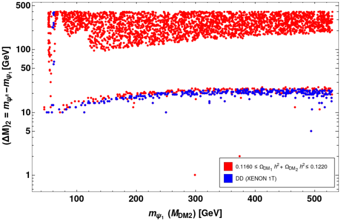
The minimal renormalizable Lagrangian for FDM having one vector-like doublet (Ψ) and one right-handed singlet (χ_R) reads:

$$\begin{aligned} \mathcal{L}^{\rm FDM} &= \overline{\Psi}_{L(R)} \left[i\gamma^\mu\left(\partial_\mu - i g_2 \frac{\sigma^a}{2} W^a_\mu - i g_1 \frac{Y'}{2} B_\mu\right)\right] \Psi_{L(R)} + \overline{\chi_R}\ (i\gamma^\mu \partial_\mu)\ \chi_R \\ &- m_\psi \overline{\Psi}\Psi - \left(\frac{1}{2} m_\chi \overline{\chi_R} (\chi_R)^c + h.c\right) - \frac{Y}{\sqrt{2}}\Big(\ \overline{\Psi_L}\ \widetilde{H}\chi_R + \ \overline{\Psi_R}\ \widetilde{H}{\chi_R}^c \end{aligned}$$

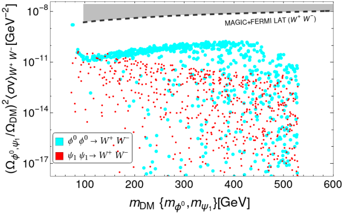
where $\Psi_{L(R)} = P_{L(R)}\Psi;\ P_{L/R} = \frac{1}{2}(1 \mp \gamma_5)$.



500
100
50
10
5
1
$(\Delta M)_1 = m_{H^\pm} - m_{H^0}$ [GeV]
100
200
300
400
500
m_{H^0} (M_{DM1}) [GeV]
$0.1160 \le \Omega_{DM_1} h^2 + \Omega_{DM_2} h^2 \le 0.1220$
DD (XENON 1T)



500
100
50
10
5
1
$(\Delta M)_2 = m_{\psi^\pm} - m_{\psi_1}$ [GeV]
100
200
300
400
500
m_{ψ_1} (M_{DM2}) [GeV]
$0.1160 \le \Omega_{DM_1} h^2 + \Omega_{DM_2} h^2 \le 0.1220$
DD (XENON 1T)



10^{-8}
10^{-11}
10^{-14}
10^{-17}
$(\Omega_{\phi^0,\psi_1}/\Omega_{DM})^2 \langle\sigma v\rangle_{W^+W^-}$ [GeV^{-2}]
MAGIC+FERMI LAT ($W^+ W^-$)
$\phi^0 \phi^0 \to W^+ W^-$
$\psi_1 \psi_1 \to W^+ W^-$
100
200
300
400
500
600
m_{DM} $\{m_{\phi^0}, m_{\psi_1}\}$[GeV]

BPs	SDM sector $\{m_{\phi^0},\ \Delta m_1,\ \lambda_L\}$	FDM sector $\{m_{\psi_1},\ \Delta m_2, \sin\theta\}$	$\Omega_{\phi^0} h^2$	$\Omega_{\psi_1} h^2$	$\sigma^{\text{eff}}_{\phi^0}$ (cm^2)	$\sigma^{\text{eff}}_{\psi_1}$ (cm^2)	BR(H_{inv})%
BP1	100, 10, 0.01	60.5, 370, 0.022	0.00221	0.1195	3.45×10^{-46}	2.03×10^{-47}	0.25
BP2	100, 10, 0.01	58.91, 285, 0.032	0.00221	0.10962	3.45×10^{-46}	5.38×10^{-47}	1.60
BP3	100, 10, 0.01	58.87, 176, 0.04	0.00221	0.11941	3.45×10^{-46}	5.00×10^{-47}	1.50
BP4	100, 10, 0.01	58.48, 190, 0.042	0.00221	0.1114	3.45×10^{-46}	7.01×10^{-47}	2.4

Table 2. Benchmark points of the model; contribution to relic density, spin-independent direct detection cross-section as well as that of invisible Higgs decay branching ratios of the DM components ϕ^0 and ψ_1 are mentioned.

Benchmarks		Collider cross-section (fb)								
		σ_{total}(OSD)			$\sigma_{\phi^+\phi^-}$(OSD)			$\sigma_{\psi^+\psi^-}$(OSD)		
$\sqrt{s}$	Points	P1	P2	P3	P1	P2	P3	P1	P2	P3
1000	BP1	232(10.8)	115(5.5)	58.5(2.75)	57.4(2.9)	28.9(1.5)	14.5(0.75)	173(8.4)	83.0(4.0)	44.0(2.0)
	BP2	276(13.4)	141(6.6)	70.0(3.3)	57.4(2.9)	28.9(1.5)	14.5(0.75)	218(10.4)	111(5.3)	55.5(2.7)
500	BP3	686(33.0)	339(15.9)	168.1(7.8)	180(8.9)	90.3(4.5)	44.3(2.3)	494(22.2)	253(11.3)	123.8(5.5)
	BP4	345(16.7)	170(8.4)	83.5(3.9)	180(8.9)	90.3(4.5)	44.3(2.3)	171.4(7.4)	82.4(3.9)	39.2(1.9)

Table 3. Signal cross-sections for HDSP pair production (OSD final state) at ILC. Total cross-section (σ_{tolal}), as well as individual contributions from SDM ($\sigma_{\phi^+\phi^-}$) and FDM ($\sigma_{\psi^+\psi^-}$) are mentioned. Three choices of beam polarisation are used: P1 $\equiv \{P_{e^-} : -0.8, P_{e^+} : +0.3\}$, P2 $\equiv \{P_{e^-} : 0, P_{e^+} : 0\}$ and P3 $\equiv \{P_{e^-} : +0.8, P_{e^+} : -0.3\}$. CM energy ($\sqrt{s}$) is in the units of GeV.

Backgrounds		Cross-section(fb)		
$\sqrt{s}$	Processes	P1	P2	P3
1 TeV	WW	296	128	18.3
	ZZ	7.5	4.4	3.5
	WWZ	1.2	0.5	0.08
500 GeV	WW	802	342	51
	ZZ	21	12	9.6
	WWZ	0.8	0.37	0.06

Table 4. Production cross-sections for $W^+(\ell^+\nu)W^-(\ell^-\bar{\nu})$, $Z(\ell^+\ell^-)Z(\nu\bar{\nu})$ and $W^+(\ell^+\nu)W^-(\ell^-\bar{\nu})Z(\nu\bar{\nu})$ background at $\sqrt{s} = 1$ TeV and 500 GeV for various polarization combinations P1, P2 and P3 (see caption of Table 3).