Multi-Component Dark Matter: Identifying at Collider

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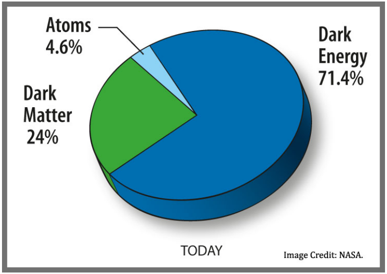
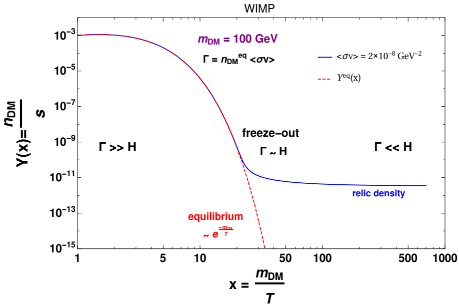
What we know about DM ?

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

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when $\Gamma << H$:

DM DM $\not\rightarrow$ SM SM

DM becomes relic.

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  - larger allowed parameter space .. (SB, PG.., JHEP 03 (2020) 090)

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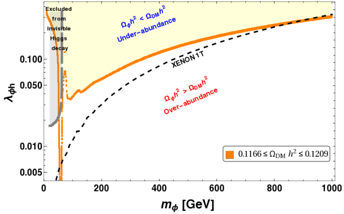

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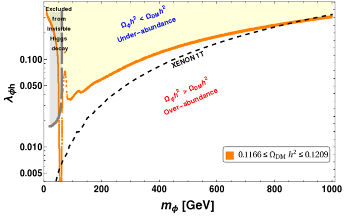

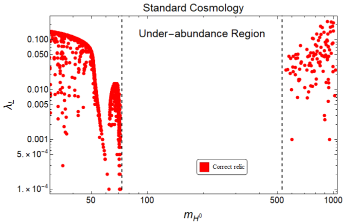

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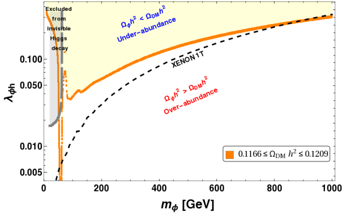

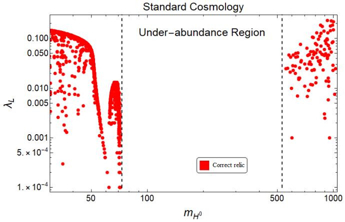

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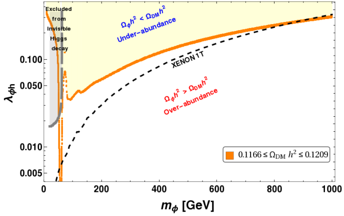

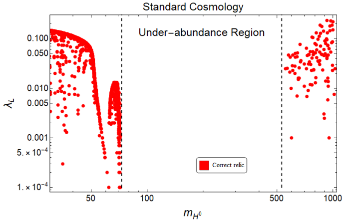

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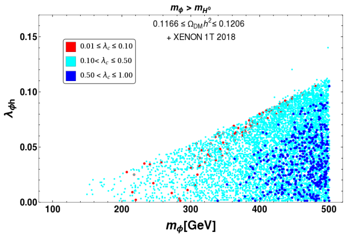

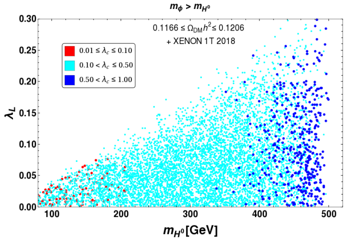

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Ref: JHEP12(2022)049 (arXiv: 2202.12097)
Subhaditya Bhattacharya, **P Ghosh**, Jayita Lahiri and Biswarup Mukhopadhyaya

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

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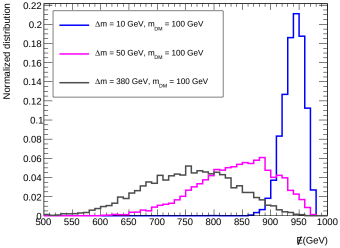

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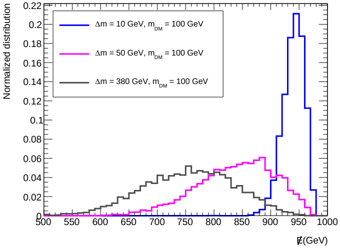

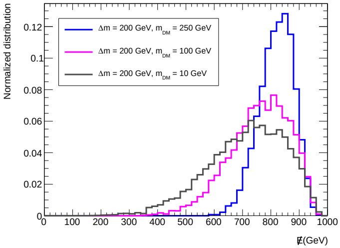

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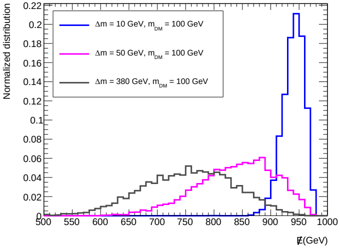

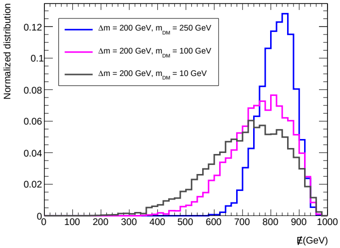

- The peak of the distribution shifts to the right with an increase in splitting (Δm) for a fixed mass $m_{\rm DM}$.
- Increasing mass ($m_{\rm DM}$) doesn't shift the peak position; it shifts the distribution endpoint.

- Two component DM with:
  - DM1: $\{X_1^0(m_{\rm DM1}),\ X_1^{\pm}(m_{\rm DM1} + \Delta m_1)\ \} :\ X_1^- \to\ \ell^-\ \overline{\nu_\ell}\ X_1^0$
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  - Both having identical collider signal: $\ell^+\ell^- + 0j+$ ME.

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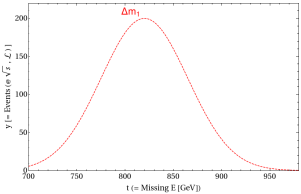

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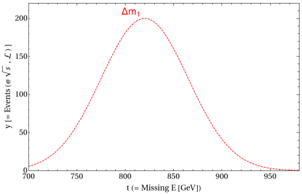

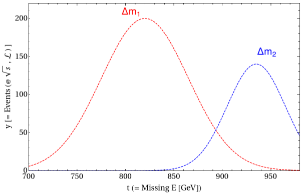

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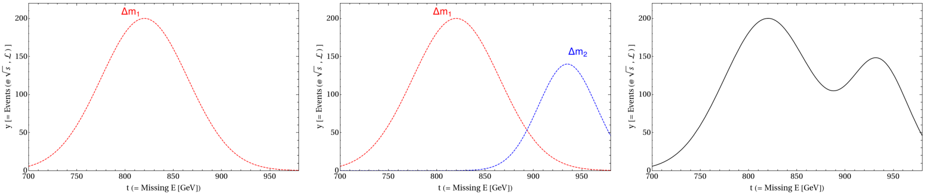

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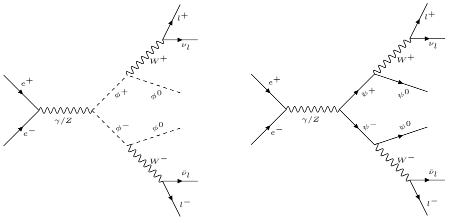

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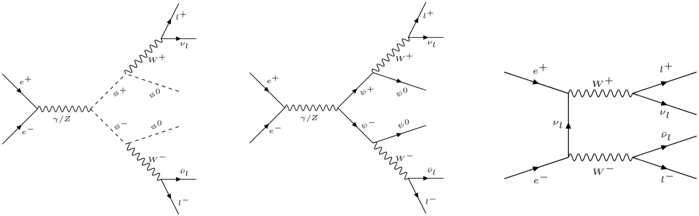

Subhaditya Bhattacharya, **PG**, Jayita Lahiri, Biswarup Mukhopadhyaya JHEP12(2022)049

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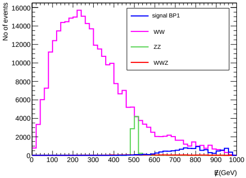

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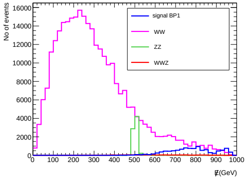

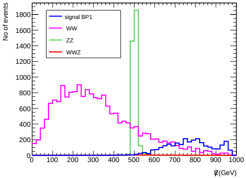

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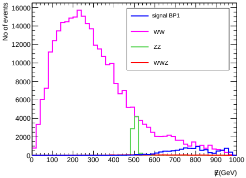

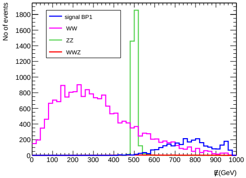

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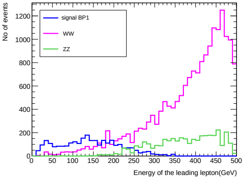

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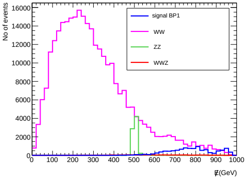

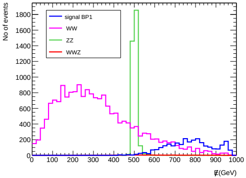

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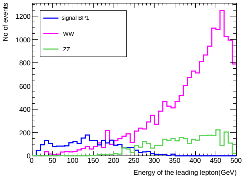

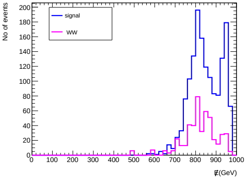

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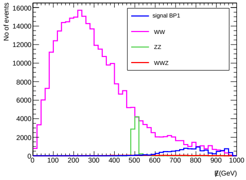

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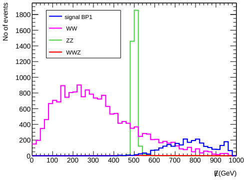

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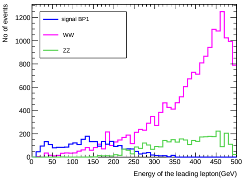
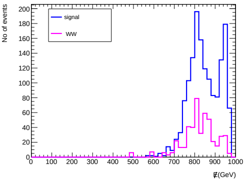
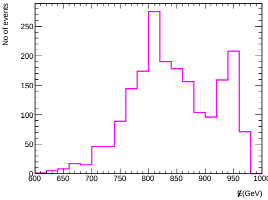


Cut1 : Without cut



Cut2: $E(\ell_1) < 150$ GeV

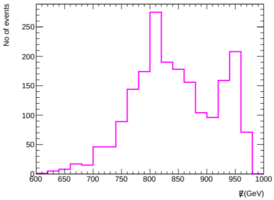


Sig+Background

- The separation of the peaks depends on Δm; while height depnd on production crosssection.
- <u>Two peak Gaussian Fitting</u> :

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

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



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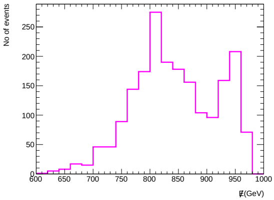

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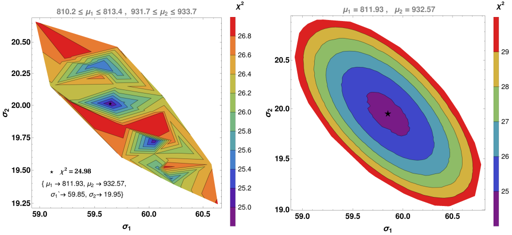

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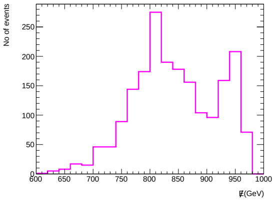

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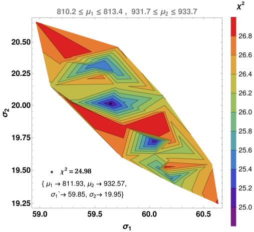

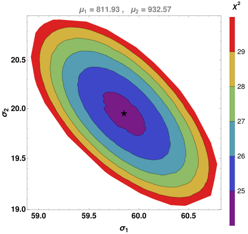

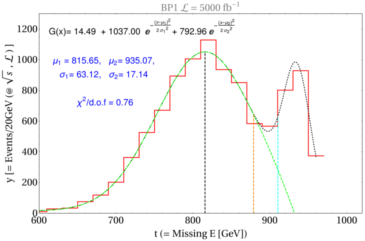

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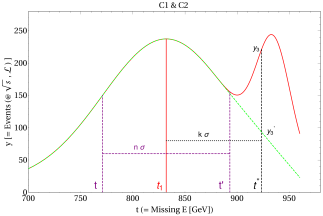
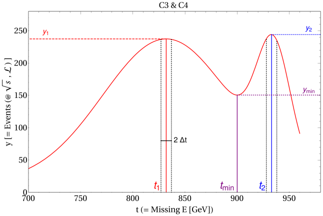




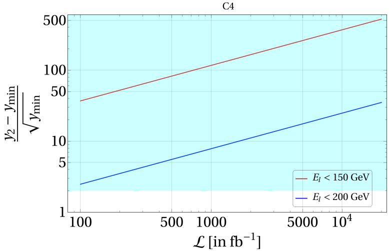
- Conditions for segregating the peaks

$$C1: \quad \Delta N_1 = \int_t^{t_1} y\,dt, \quad \Delta N_2 = \int_{t_1}^{t'} y\,dt$$

$$R_{C1} = \frac{|\Delta N_2 - \Delta N_1|}{\sqrt{\Delta N_1}} > 2.$$

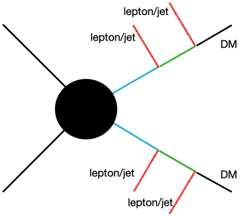
$$C2: \quad R_{C2} = \frac{y(t'') - y'(t'')}{\sqrt{y'(t'')}} > 2.$$

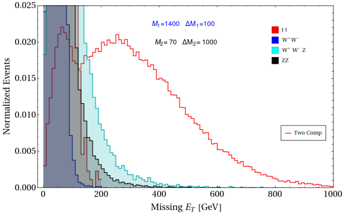
$$C4: \quad R_{C4} = \frac{y(t_2) - y(t_{min})}{\sqrt{y(t_{min})}} > 2.$$



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.

Work in Progress ....

• The key variables that play a role in producing distinguishable peaks are

- both of the DM masses $(m_{\rm DM1}, m_{\rm DM2})$; their mass-splitting with the corresponding HDSPs $(\Delta m_1, \Delta m_2)$; and their production cross-sections $(\sigma_{X_1^+ X_1^-}, \sigma_{X_2^+ X_2^-})$.

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thank you!

Ref: JHEP12(2022)049(arXiv:2202.12097) **pghoshiitg@gmail.com**

The minimal renormalizable Lagrangian for this model then reads,

$$\mathcal{L} \supset \mathcal{L}^{\rm SDM} + \mathcal{L}^{\rm FDM}. \tag{3}$$

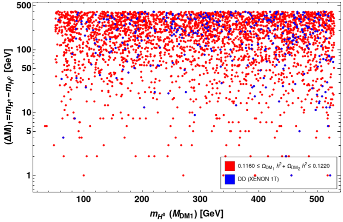
The Lagrangian for the SDM sector, having inert scalar doublet Φ can be written as :

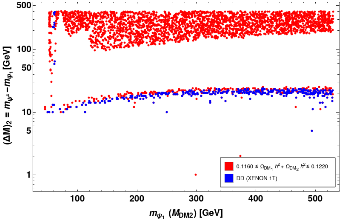
$$\begin{aligned}\mathcal{L}^{\rm SDM} &= \left|\left(\partial^\mu - ig_2\frac{\sigma^a}{2}W^{a\mu} - ig_1\frac{Y}{2}B^\mu\right)\Phi\right|^2 - V(\Phi,H)\,; \\ V(\Phi,H) &= \mu_\Phi^2(\Phi^\dagger\Phi) + \lambda_\Phi(\Phi^\dagger\Phi)^2 + \lambda_1(H^\dagger H)(\Phi^\dagger\Phi) + \lambda_2(H^\dagger\Phi)(\Phi^\dagger H) \\ &\quad + \frac{\lambda_3}{2}[(H^\dagger\Phi)^2 + h.c.]\ .\end{aligned}$$

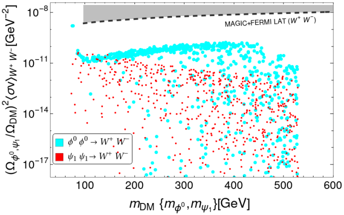
The minimal renormalizable Lagrangian for FDM having one vector-like doublet (Ψ) and one right-handed singlet (χ_R) reads:

$$\begin{aligned}\mathcal{L}^{\rm FDM} &= \overline{\Psi}_{L(R)}\ [i\gamma^\mu(\partial_\mu - ig_2\frac{\sigma^a}{2}W^a_\mu - ig_1\frac{Y'}{2}B_\mu)]\ \Psi_{L(R)} + \overline{\chi_R}\ (i\gamma^\mu\partial_\mu)\ \chi_{R} \\ &- m_\psi\overline{\Psi}\Psi - \left(\frac{1}{2}m_\chi\overline{\chi_R}(\chi_R)^c + h.c\right) - \frac{Y}{\sqrt{2}}\Big(\ \overline{\Psi_L}\ \widetilde{H}\chi_R + \ \overline{\Psi_R}\ \widetilde{H}\chi_R{}^c\end{aligned}$$

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


$(\Delta M)_1 = m_{H^\pm} - m_{H^0}$ [GeV]
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)


$(\Delta M)_2 = m_{\psi^\pm} - m_{\psi_1}$ [GeV]
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)


$(\Omega_{\phi^0,\psi_1}/\Omega_{DM})^2 \langle\sigma v\rangle_{W^+W^-}$ [GeV^{-2}]
m_{DM} $\{m_{\phi^0}, m_{\psi_1}\}$[GeV]
MAGIC+FERMI LAT ($W^+ W^-$)
$\phi^0 \phi^0 \to W^+ W^-$
$\psi_1 \psi_1 \to W^+ W^-$

BPs	SDM sector $\{m_{\phi^0},\ \Delta m_1,\ \lambda_L\}$	FDM sector $\{m_{\psi_1},\ \Delta m_2, \sin\theta\}$	$\Omega_{\phi^0} h^2$	$\Omega_{\psi_1} h^2$	$\sigma^{\rm eff}_{\phi^0}$ (cm^2)	$\sigma^{\rm eff}_{\psi_1}$ (cm^2)	BR($H_{\rm inv}$)%
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)								
		$\sigma_{\rm total}$(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 ($\sigma_{\rm tolal}$), 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).