Leptophilic Dark Matter at International Linear Collider

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Based on arXiv:2110.06903 [hep-ph]

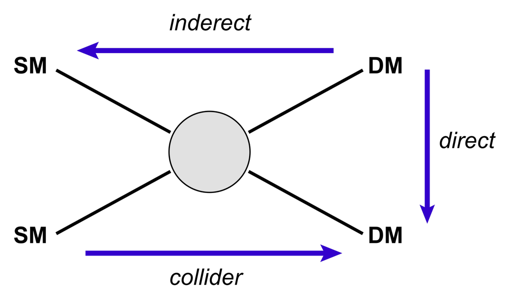
1. Introduction

Motivation:

- After the Higgs searches at the LHC, the dark matter searches is the most important physics problem to be tackled at Linear Collider and LHC.
- Interacts gravitationally, charge neutral, stable.
- Limited knowledge on other properties.

Search Strategy:

- Direct Detection: XENON1T, SuperCDMS, PANDAX-4T etc.
- Indirect Detection: AMS-02, Fermi-LAT etc.
- Collider Seach: LHC, Belle, ILC, CLIC etc.



2. Effective Model

- Lepton collider is a good place to probe the effective theories compared to a hadron one.
- New physics (NP) scale will be greater the hard scattering CM energy.
- Definite energy initial states can be controlled, polarisation of beams possible.

3. Leptophilic Effective Model

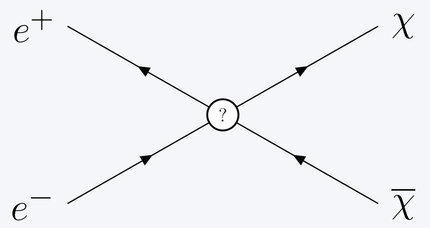
$$\mathcal{L}_{\rm eff} = \frac{1}{\Lambda^2}\sum_j \left(\overline{\chi}\Gamma^j_\chi \chi\right)\left(\overline{\ell}\Gamma^j_\ell \ell\right)$$

Scalar-Pseudoscalar (SP) type : $\Gamma_\chi = c^\chi_S + i c^\chi_P \gamma_5\,,\quad \Gamma_\ell = c^e_S + i c^e_P \gamma_5\,,$

Vector-Axial vector (VA) type : $\Gamma^\mu_\chi = \left(c^\chi_V + c^\chi_A \gamma_5\right)\gamma^\mu\,,\quad \Gamma_{\ell\mu} = \left(c^e_V + c^e_A\gamma_5\right)\gamma_\mu\,,$

Tensor-Axial Tensor (TAT) type : $\Gamma^{\mu\nu}_\chi = \left(c^\chi_T + i c^\chi_{AT}\gamma_5\right)\sigma^{\mu\nu}\,,\quad \Gamma_{\ell\mu\nu} = \sigma_{\mu\nu}\,,$

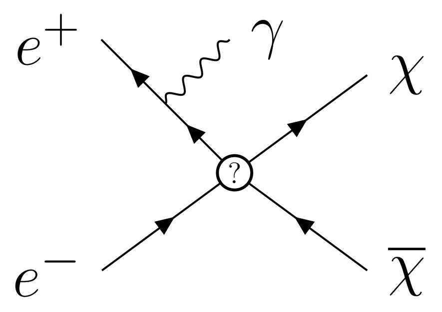
- For an e^+-e^- collider, $\ell = e$ and we took $c_i = 1$.
- No specific realization of the operators – model-independent.
- Cut-off scale, $\Lambda = \frac{m_{med}}{\sqrt{g_e g_\chi}}$
- Need for a visible particle.



4. Mono-photon Channel

Backgrounds

- Irreducible: (radiative) neutrino pair-prooduction ($\nu\overline{\nu}+\gamma$), (radiative) Bhabha scattering ($e^+e^- + \gamma$)
- Higher order: $\nu\overline{\nu} + N\gamma$, $e^+e^- + N\gamma$; neglected.



Simulation:

- Signals and the neutrino-pair background events are generated using `CalcHEP` with proper implementation of *ISR* and *beamstrahlung*.
- Bhabha events are simulated with `Whizard`. *ISR* photons are simulated with standard routine in Whizard and *beamstrahlung* effects are simulated with the `CIRCE2` beam spectrum files.
- Fast Detector simulation with `Delphes 3` with a `SiD`-based configuration card.

5. Effect of Polarisation

Process type	Unpolarized cross-section (fb)	Polarization $P(e^-, e^+)$	Polarized cross-section (fb) $(+,+)$	$(+,-)$	$(-,+)$	$(-,-)$
$\nu\overline{\nu}\gamma$	4782	(80, 0)	1106	1106	8506	8506
		(80, 20)	1268	963	10160	6793
		(80, 30)	1393	860	10993	5931
$e^-e^+\gamma$	68439	(80, 0)	67920	67920	68867	68867
		(80, 20)	67909	68386	69285	68297
		(80, 30)	67809	68566	69502	68181
SP-type	25.5	(80, 0)	25.5	25.5	25.5	25.5
		(80, 20)	29.6	21.4	21.4	29.6
		(80, 30)	**31.6**	19.4	19.4	31.6
VA-type	34.3	(80, 0)	61.7	61.7	6.9	6.9
		(80, 20)	49.4	74.1	5.5	8.2
		(80, 30)	43.2	**80.3**	4.8	8.9
TAT-type	36.5	(80, 0)	36.5	36.5	36.5	36.5
		(80, 20)	42.3	30.6	30.6	42.3
		(80, 30)	**45.2**	27.7	27.7	45.2

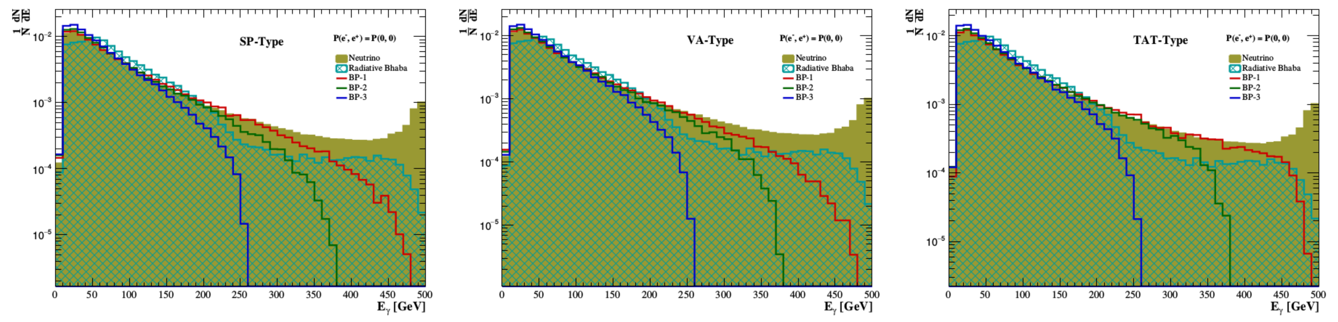
Electron Beam:

1. Neutrino pair background reduced considerably (23%) by RH electron polarisation.
2. Bhabha background is NOT affected by beam polarisation.
3. Electron beam polarisation doesn't affect the signals (SP, TAT).
4. VA type behaves otherwise.

Positron Beam:

1. LH positron beams further reduces the neutrino background.
2. SP and TAT-type CSs get better with RH positron beam.
3. VA-type are best with $P(e^-, e^+) = (+80\%, +30\%)$.

6. Analysis and Results



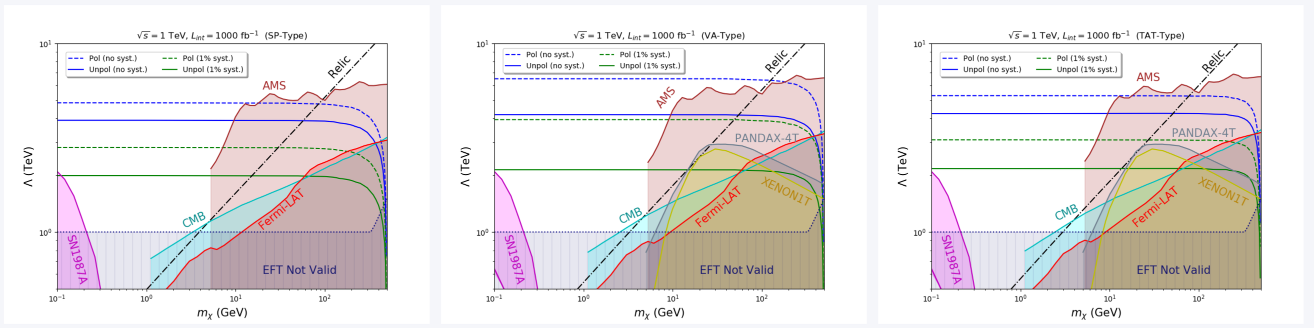
	BP1	BP2	BP3
Definition	$m_\chi = 100$ GeV, $\Lambda = 3$ TeV	$m_\chi = 250$ GeV, $\Lambda = 3$ TeV	$m_\chi = 350$ GeV, $\Lambda = 3$ TeV
Baseline selection	$E_\gamma > 10$ GeV, $\lvert\eta_\gamma\rvert < 2.45$, $P_T^{\rm miss} > 10$ GeV		
SP-type			
Cut-1	$E_\gamma < 450$ GeV	$E_\gamma < 340$ GeV	$E_\gamma < 250$ GeV
Cut-2	$\lvert\eta_\gamma\rvert < 1.6$		
Cut-3	$P_T^{\rm miss} < 450$ GeV	$P_T^{\rm miss} < 340$ GeV	$P_T^{\rm miss} < 240$ GeV
Cut-4	$P_T^{\rm frac} < 1.3$		
Cut-5	$1.1 < \Delta R_{\gamma,{\rm MET}} < 4.5$		

BeamCal veto is effected using the selection efficiency from full detector simulation performed by M. Habermehl et. al. [PRD 101 (2020) 075053].

Operator type	Signal significance for $\mathcal{L}_{\rm int} = 1000\,{\rm fb}^{-1}$: Unpolarized beams BP-1	BP-2	BP-3	Polarized beams BP-1	BP-2	BP-3
SP-type	8.1 (0.6)	5.8 (0.4)	3.5 (0.3)	18.1 (2.4)	13.0 (1.7)	7.8 (1.0)
VA-type	10.9 (0.8)	8.5 (0.6)	5.6 (0.4)	24.9 (3.2)	19.4 (2.5)	12.9 (1.7)
TAT-type	11.8 (0.8)	10.8 (0.8)	8.5 (0.6)	26.2 (3.5)	24.1 (3.2)	19.2 (2.6)

Figure 1. Signal significance without (with) 1% systematics.

7. Sensitivities

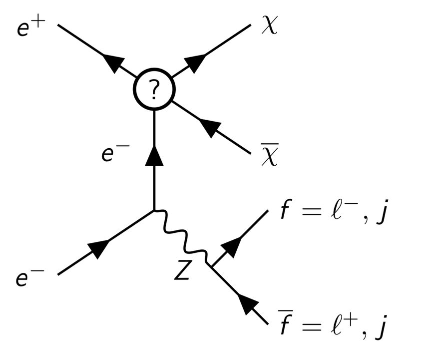


- The VA-type operator delivers best sensitivity with optimally polarised beams Λ reaches upto 6.5 TeV (4TeV) without (with) 1% systematics.
- χ-e^- scattering ($\sim \mathcal{O}(10^{-47})$cm^2) translates into very weak direct bound from Indirect searches like Xenon1T ($\sim \mathcal{O}(10^{-39})$cm^2) or DARKSPHERE ($\sim \mathcal{O}(10^{-42})$cm^2).
- χ-N scattering dominates over χ-e^- scattering. (J. Kopp et.al. PRD 80 (2009) 083502)
- Indirect detection (e.g. AMS-02) and thermal relic bounds put strong constraints.
- Lighter mass dark matter is allowed with non-thermal history.

8. Mono-Z

Backgrounds

- Leptonic:
  - $\nu\bar{\nu}\ell^+\ell^-$ ($\ell^\pm \equiv e^\pm, \mu^\pm$)
- Hadronic:
  - $\nu\bar{\nu}jj$, $\ell\nu jj$ ($j \equiv u, c, d, s, b$)
  - Reducible: $e^+e^- \to t\bar{t}$; neglected.



Simulation:

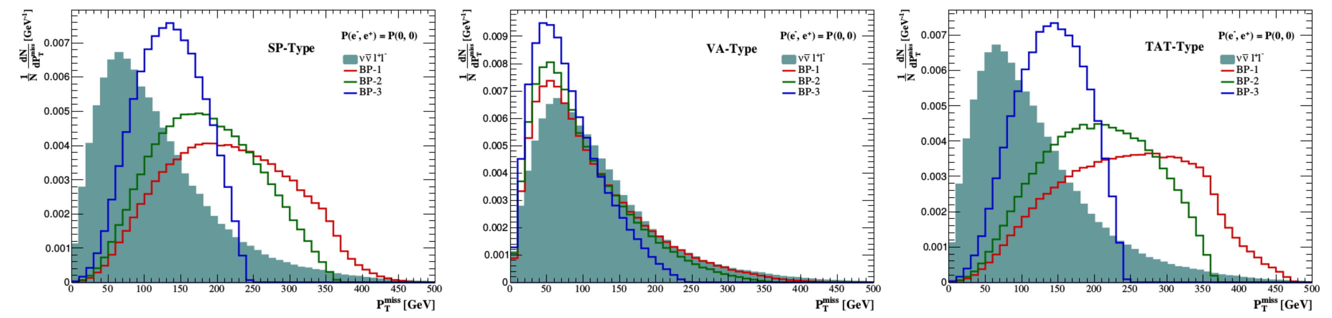
- Signals and background events are generated with `MadGraph5`.
- Hadronizations are done with `Pythia8`.
- Fast Detector simulation is done with `Delphes 3`.
  - `anti-kT` jet clustering algorithm, $p_T > 10$ GeV and $R = 0.4$ using `FastJet`.

9. Effect of Polarisation

- Under beam polarisation the behaviour of signal and backgrounds are identical for both the channels as it is for the mono-photon channel.

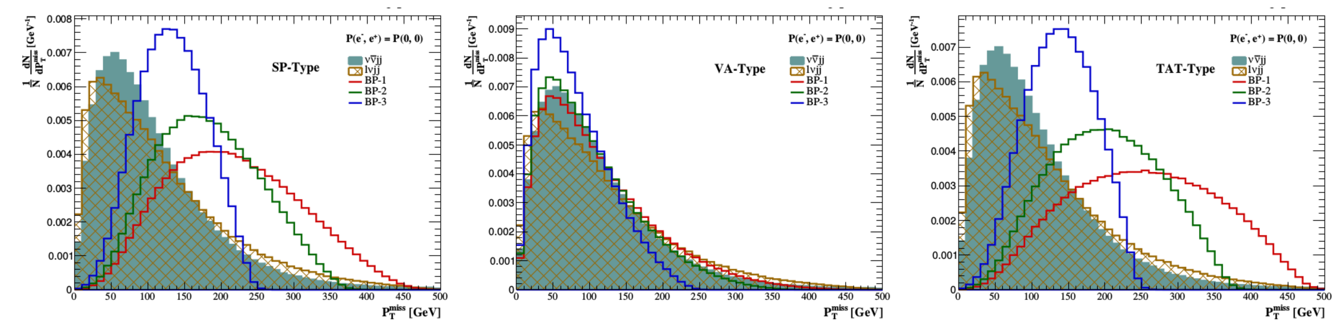
10. Analysis and Results

Leptonic:



Operator Type	Signal significance for $\mathcal{L}_{\rm int} = 1000\,{\rm fb}^{-1}$: Unpolarized beams BP-1	BP-2	BP-3	Polarized beams BP-1	BP-2	BP-3
SP-type	1.7 (1.3)	0.7 (0.5)	0.1 (0.1)	3.8 (3.6)	1.7 (1.5)	0.3 (0.3)
VA-type	0.2 (0.1)	0.1 (0.1)	0.1 (0.1)	0.5 (0.4)	0.4 (0.3)	0.2 (0.2)
TAT-type	4.5 (3.9)	2.4 (1.9)	0.6 (0.5)	9.4 (9.1)	5.4 (5.1)	1.3 (1.3)

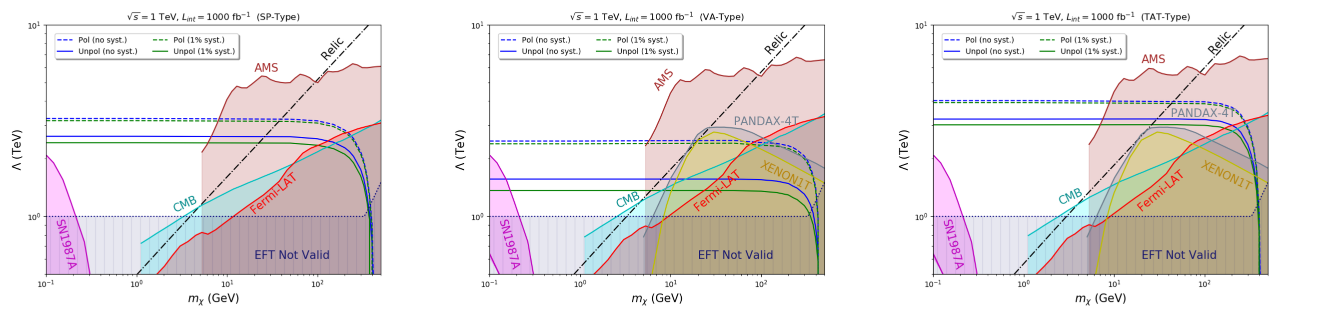
Hadronic:



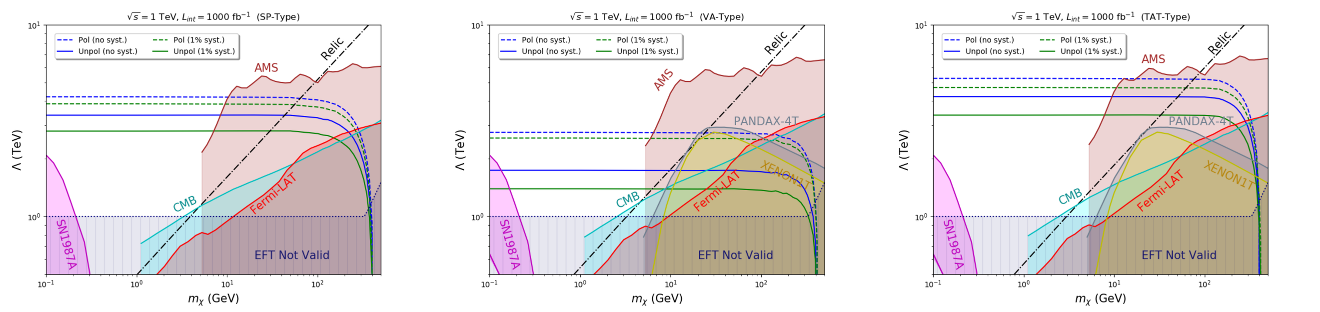
Operator types	Signal significance for $\mathcal{L}_{\rm int} = 1000\,{\rm fb}^{-1}$: Unpolarized beams BP-1	BP-2	BP-3	Polarized Beam BP-1	BP-2	BP-3
SP-type	4.7 (3.3)	1.5 (1.0)	0.3 (0.2)	10.3 (9.1)	3.6 (3.1)	0.8 (0.6)
VA-type	0.4 (0.2)	0.3 (0.1)	0.1 (0.1)	0.2 (0.1)	0.1 (0.1)	0.1 (0.04)
TAT-type	14.2 (10.4)	5.8 (3.7)	1.2 (0.7)	27.7 (25.6)	12.9 (11.1)	2.8 (2.3)

11. Sensitivities

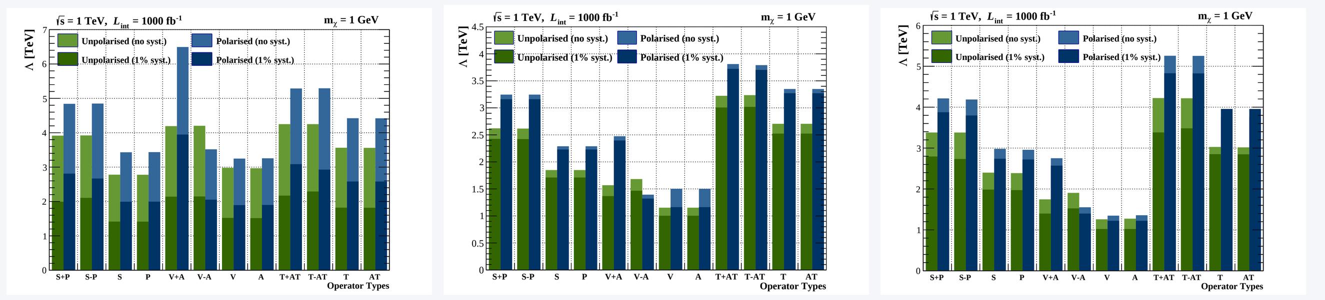
Leptonic:



Hadronic:



12. Summary



- ILC is a good choice to probe EFT theory with cut-off scale larger than CM energy.
- Mixed couplings show off better performance than single operators.
- Higher mass region highly constrained by direct and indirect detection experiments allowed by relic density bound.
- Low mass region disfavoured by thermal relic bound.
- Non-thermal DMs are still valid and doesn't affect our model.