Probing Leptopilic Dark Matter at 1TeV ILC with Effective Operators

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Outline

Introduction

The Effective Model

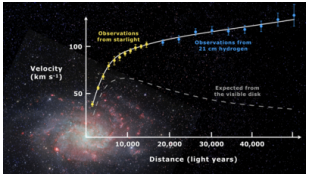
Mono-photon Channel

Mono-Z Channel

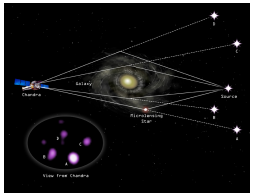
Conclusion

Introduction

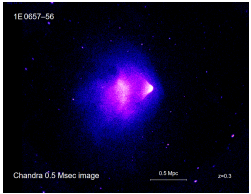
- After the Higgs searches at the LHC, the dark matter searches is the most important physics problem to be tackled at Linear Collider and LHC.
- Cosmological observations, e.g. velocity dispersion of Coma clusters (Zwicky,1933), galaxy rotation curves, gravitational lensing, bullet-cluster, advocates the presence of Dark Matter.



Spiral Galaxy



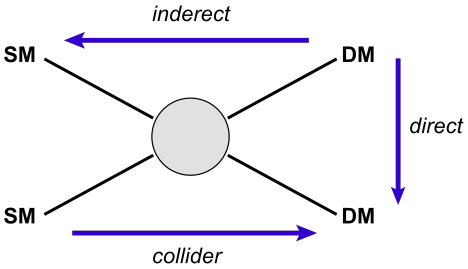
Gravitational Lensing



Bullet Cluster

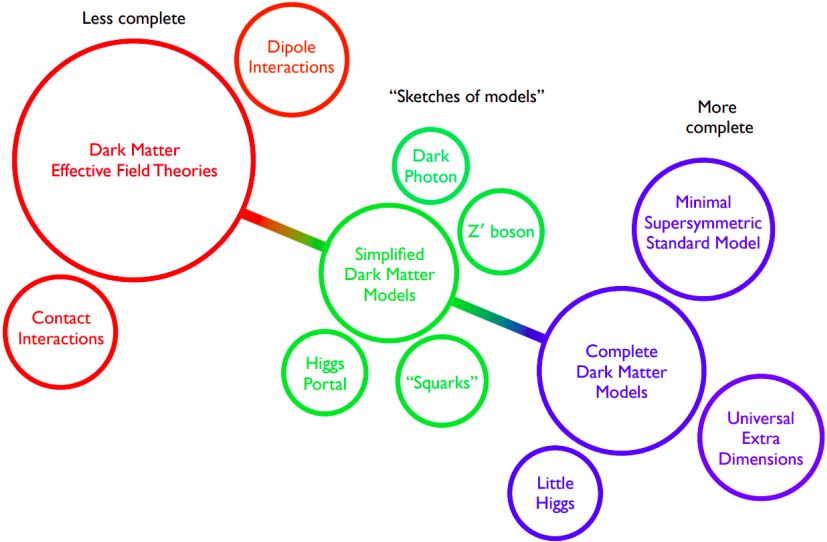
- Interacts gravitationally, charge neutral, stable.
- Little known about he properties of the DM particles.

Strategy



- **3 classes** of search strategy are being employed:
- Despite the effect, DM are yet to be detected.
- Direct and indirect detection facilities with higher sensitivities will come up.
- LHC with higher luminosities (HL-LHC), higher CM energy (HE-LHC) coming up. e^+e^- linear colliders are coming up.
- In order to interpret the limits from collider searches and to relate these bounds to the constraints from direct and indirect detections one needs a theory.

Different Models

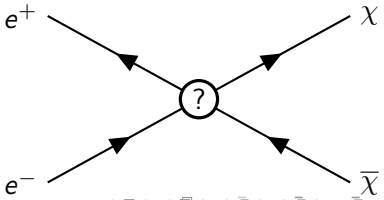


Leptophilic Effective Model

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

Scalar-Pseudoscalar (SP) type :	$\Gamma_\chi = c_S^\chi + ic_P^\chi\gamma_5\,,$	$\Gamma_\ell = c_S^e + ic_P^e\gamma_5\,,$
Vector-Axial vector (VA) type :	$\Gamma_\chi^\mu = \left(c_V^\chi + c_A^\chi\gamma_5\right)\gamma^\mu\,,$	$\Gamma_{\ell\mu} = \left(c_V^e + c_A^e\gamma_5\right)\gamma_\mu\,,$
Tensor-Axial Tensor (TAT) type :	$\Gamma_\chi^{\mu\nu} = \left(c_T^\chi + ic_{AT}^\chi\gamma_5\right)\sigma^{\mu\nu}\,,$	$\Gamma_{\ell\mu\nu} = \sigma_{\mu\nu}\,,$

- 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.

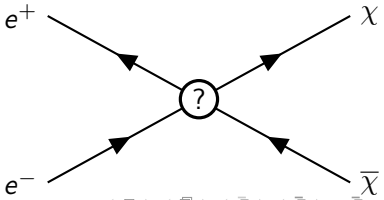


Leptophilic Effective Model

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

Scalar-Pseudoscalar (S+P) type :	$\Gamma_\chi = c^\chi_S + ic^\chi_P\gamma_5\,,$	$\Gamma_\ell = c^e_S + ic^e_P\gamma_5\,,$
Vector-Axial vector (V+A) type :	$\Gamma^\mu_\chi = \left(c^\chi_V + c^\chi_A\gamma_5\right)\gamma^\mu\,,$	$\Gamma_{\ell\mu} = \left(c^e_V + c^e_A\gamma_5\right)\gamma_\mu\,,$
Tensor-Axial Tensor (T+AT) type :	$\Gamma^{\mu\nu}_\chi = \left(c^\chi_T + ic^\chi_{AT}\gamma_5\right)\sigma^{\mu\nu}\,,$	$\Gamma_{\ell\mu\nu} = \sigma_{\mu\nu}\,,$

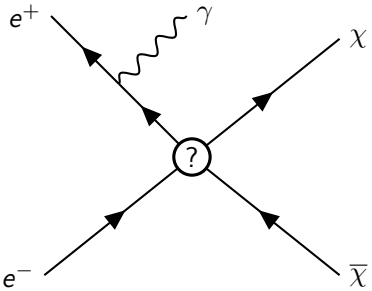
- For an e^+-e^- collider, $\ell = e$ and we took $c_i = 1$.
- No specific realization of the operators – model-independent.
- Cut-off scale, $\Lambda = \frac{m_{med}}{\sqrt{g_e g_\chi}}$
- Need for a visible particle.



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 configuration card based on `SiD` detector.

Polarisation

Process type	Unpol CS (fb)	Polarization $P(e^-, e^+)$	Polarized cross-section (fb) $(+,+)$	$(+,-)$	$(-,+)$	$(-,-)$
$\nu\bar{\nu}\gamma$	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:
  - Neutrino pair background reduced considerably by RH electron polarisation.
  - Bhabha background is NOT affected by beam polarisation.
  - Electron beam polarisation doesn't affect the signals (SP, TAT).
  - VA type behaves otherwise.
- Positron Beam:
  - LH positron beams further reduces the neutrino background.
  - SP and TAT-type CSs are RH positron beam.
  - VA-type are best with $P(e^-, e^+) = (+80\%, +30\%)$.

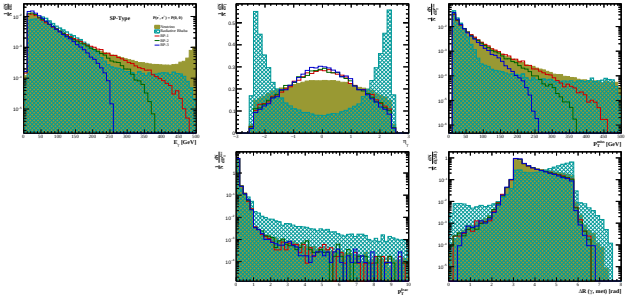
Analysis and Results

	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	$1.1 < \Delta R_{\gamma,\rm MET} < 4.5$		
VA-type			
Cut-1	$E_\gamma < 440$ GeV	$E_\gamma < 350$ GeV	$E_\gamma < 250$ GeV
Cut-2	$\lvert\eta_\gamma\rvert < 1.7$		
Cut-3	$P_T^{\rm miss} < 400$ GeV	$P_T^{\rm miss} < 340$ GeV	$P_T^{\rm miss} < 250$ GeV
Cut-4	$P_T^{\rm frac} < 1.2$		
Cut-5	$1.1 < \Delta R_{\gamma,\rm MET} < 4.5$		
TAT-type			
Cut-1	$E_\gamma < 460$ GeV	$E_\gamma < 360$ GeV	$E_\gamma < 230$ GeV
Cut-2	$\lvert\eta_\gamma\rvert < 1.7$		
Cut-3	$P_T^{\rm miss} < 450$ GeV	$P_T^{\rm miss} < 350$ GeV	$P_T^{\rm miss} < 230$ GeV
Cut-4	$P_T^{\rm frac} < 1.2$		
Cut-5	$1.1 < \Delta R_{\gamma,\rm MET} < 4.4$		

$$\mathrm{Sig} = \frac{S}{\sqrt{S + B + (\epsilon B)^2}}$$

ϵ is the systematic error

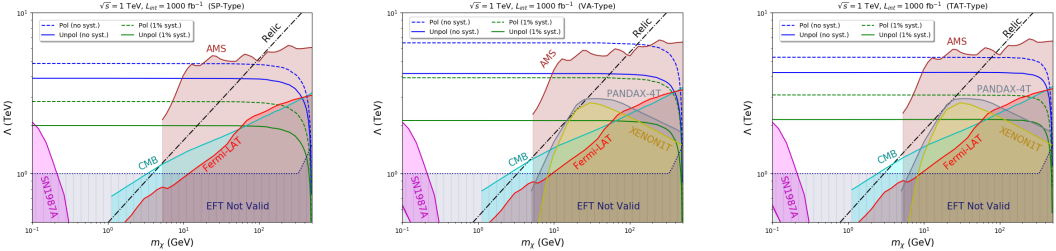
- 1% systematic error for background (both) estimation.



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			Polarized beams		
	BP-1	BP-2	BP-3	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)

Sensitivities

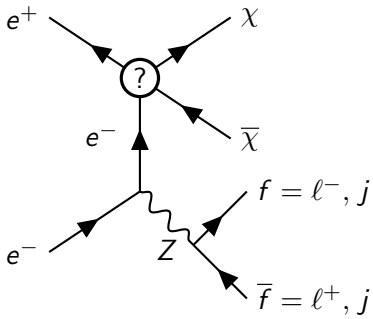


- The VA-type operator delivers best sensitivity with optimally polarised beams Λ reaches upto 6.5 TeV (4TeV) without (with) 1% systematics.
- χ-e^- scattering ($\sim \mathcal{O}(10^{-47})$cm^2) translates into very weak direct bound from Indirect searches like Xenon1T ($\sim \mathcal{O}(10^{-39})$cm^2) 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 stringent constraints.
- Lighter mass dark matter is allowed with non-thermal history.

Mono-Z Channel

Backgrounds

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

Polarisation

Leptonic Channel

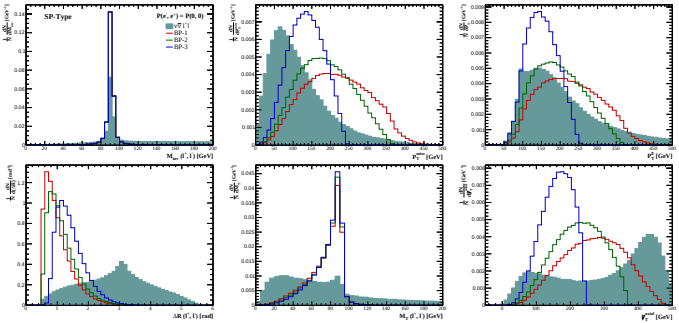
Process type	Unpol CS (fb)	Polarization $P(e^-, e^+)$	Polarized cross-section (fb) $(+,+)$	$(+,-)$	$(-,+)$	$(-,-)$
$\nu\bar{\nu}\ell^-\ell^+$	420	$(80, 0)$	116	116	723	723
		$(80, 20)$	135	98	856	590
		$(80, 30)$	145	88	926	523
SP-Type	0.28	$(80, 0)$	0.26	0.26	0.25	0.25
		$(80,20)$	0.29	0.22	0.21	0.29
		$(80, 30)$	**0.32**	0.19	0.19	0.32
VA-Type	0.08	$(80, 0)$	0.15	0.15	0.02	0.02
		$(80,20)$	0.12	0.18	0.01	0.02
		$(80, 30)$	0.11	**0.19**	0.01	0.02
TAT-Type	0.68	$(80, 0)$	0.62	0.62	0.62	0.62
		$(80,20)$	0.72	0.52	0.52	0.72
		$(80, 30)$	**0.77**	0.47	0.47	0.77

Hadronic Channel

Process type	Unpol CS (fb)	Pol. $P(e^-, e^+)$	Polarized cross-section (fb) $(+,+)$	$(+,-)$	$(-,+)$	$(-,-)$
$\nu\bar{\nu}jj$	798	$(80, 0)$	178	178	1415	1415
		$(80, 20)$	206	151	1689	1134
		$(80, 30)$	219	136	1833	989
$jj\ell\nu$	1186	$(80, 0)$	302	302	2061	2061
		$(80, 20)$	359	246	2446	1685
		$(80, 30)$	386	216	2635	1492
SP-Type	2.78	$(80, 0)$	2.57	2.57	2.58	2.58
		$(80, 20)$	2.98	2.15	2.15	2.97
		$(80, 30)$	**3.17**	1.95	1.95	3.17
VA-Type	0.83	$(80, 0)$	1.35	1.35	0.15	0.15
		$(80, 20)$	1.07	1.61	0.12	0.18
		$(80, 30)$	0.94	**1.76**	0.10	0.19
TAT-Type	6.77	$(80, 0)$	6.22	6.22	6.21	6.21
		$(80, 20)$	7.23	5.23	5.24	7.21
		$(80, 30)$	**7.72**	4.73	4.73	7.69

Results (Leptonic)

	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
BS	OSSF lepton-pairs with $P_{T,\ell} > 20$ GeV, $\lvert\eta_\ell\rvert < 2.45$		
SP-type			
Cut-1	$70 \text{ GeV} \leq M_{\rm inv}(\ell^-\ell^+) \leq 110$ GeV		
Cut-2	$160 \text{ GeV} < \not{E}_T$	$115 \text{ GeV} < \not{E}_T < 350$ GeV	$100 \text{ GeV} < \not{E}_T < 230$ GeV
Cut-3	$\Delta\eta_{\ell\ell} < 1.35$, $\Delta\phi_{\ell\ell} < 1.3$ rad		
Cut-4	$M_T(\ell^-\ell^+) > 60$ GeV		
Cut-5	$100 \text{ GeV} < \not{p}_T^{\rm axial} < 435$ GeV	$115 \text{ GeV} < \not{p}_T^{\rm axial} < 350$ GeV	$100 \text{ GeV} < \not{p}_T^{\rm axial} < 230$ GeV
VA-type			
Cut-1	$70 \text{ GeV} \leq M_{\rm inv}(\ell^-\ell^+) \leq 110$ GeV		
Cut-2	$P_T^{\ell\ell} < 360$ GeV	$P_T^{\ell\ell} < 270$ GeV	$P_T^{\ell\ell} < 215$ GeV
Cut-3	$\Delta\eta_{\ell\ell} < 1.2$, $\Delta\phi_{\ell\ell} < 2.6$ rad		
Cut-4	$M_T(\ell^-\ell^+) > 35$ GeV		
Cut-5	$60 \text{ GeV} < \not{p}_T^{\rm axial} < 380$ GeV	$60 \text{ GeV} < \not{p}_T^{\rm axial} < 290$ GeV	$60 \text{ GeV} < \not{p}_T^{\rm axial} < 220$ GeV
TAT-type			
Cut-1	$70 \text{ GeV} \leq M_{\rm inv}(\ell^-\ell^+) \leq 110$ GeV		
Cut-2	$210 \text{ GeV} < \not{E}_T$	$165 \text{ GeV} < \not{E}_T < 360$ GeV	$110 \text{ GeV} < \not{E}_T < 230$ GeV
Cut-3	$\Delta\eta_{\ell\ell} < 1.2$, $\Delta\phi_{\ell\ell} < 1.2$ rad		
Cut-4	$M_T(\ell^-\ell^+) > 60$ GeV		
Cut-5	$100 \text{ GeV} < \not{p}_T^{\rm axial} < 475$ GeV	$100 \text{ GeV} < \not{p}_T^{\rm axial} < 370$ GeV	$100 \text{ GeV} < \not{p}_T^{\rm axial} < 240$ GeV



- Around (50-60)% signal events are kept whereas more than 96% background events are removed.

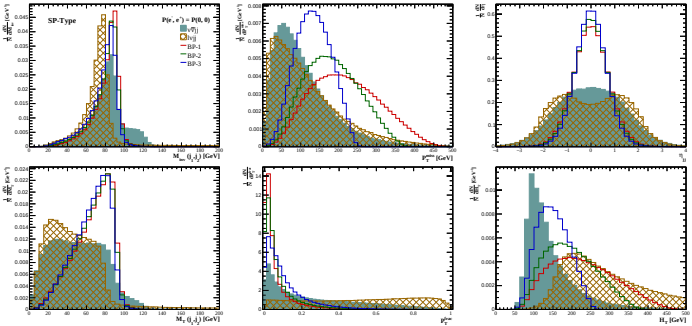
$$\text{Sig} = \frac{S}{\sqrt{S + B + (\epsilon B)^2}}$$

- 1% systematic error for background estimation.

Operator Type	Signal significance for $\mathcal{L}_{\rm int} = 1000\,\text{fb}^{-1}$					
	Unpolarized beams			Polarized beams		
	BP-1	BP-2	BP-3	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)

Results (Hadronic)

	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
BS	$P_{T,j} > 20$ GeV, $\lvert\eta_j\rvert < 2.45$		
SP-type			
Cut-1	85 GeV $\leq M_{inv}(jj) \leq 100$ GeV		
Cut-2	250 GeV $< \not{E}_T$	200 GeV $< \not{E}_T < 330$ GeV	110 GeV $< \not{E}_T < 230$ GeV
Cut-3	$\lvert\eta_j\rvert < 1.2$		
Cut-4	$\lvert\Delta R_{jj}\rvert < 1.5$		
Cut-5	$M_T(\ell\nu j) > 60$ GeV		
Cut-6	$P_T^{frac} < 0.16$		
Cut-7	250 GeV $< P_T^{axial} < 450$ GeV	220 GeV $< P_T^{axial} < 340$ GeV	110 GeV $< P_T^{axial} < 230$ GeV
Cut-8	$H_T < 460$ GeV	$H_T < 340$ GeV	$H_T < 250$ GeV
VA-type			
Cut-1	84 GeV $\leq M_{inv}(jj) \leq 98$ GeV		
Cut-2	$P_T^Z < 310$ GeV	$P_T^Z < 280$ GeV	$P_T^Z < 180$ GeV
Cut-3	$\lvert\eta_j\rvert < 1.$		
Cut-4	$\lvert\Delta R_{jj}\rvert < 1.6$		
Cut-5	$M_T(\mu j\nu) > 55$ GeV		
Cut-6	$P_T^{frac} < 0.2$		
Cut-7	100 GeV $< P_T^{axial} < 400$ GeV	110 GeV $< P_T^{axial} < 300$ GeV	50 GeV $< P_T^{axial} < 240$ GeV
Cut-8	$H_T < 330$ GeV	$H_T < 290$ GeV	$H_T < 210$ GeV
TAT-type			
Cut-1	85 GeV $\leq M_{inv}(jj) \leq 100$ GeV		
Cut-2	220 GeV $< \not{E}_T < 450$ GeV	180 GeV $< \not{E}_T < 370$ GeV	120 GeV $< \not{E}_T < 240$ GeV
Cut-3	$\lvert\eta_j\rvert < 0.8$		
Cut-4	$\lvert\Delta R_{jj}\rvert < 1.5$		
Cut-5	$M_T(\mu j\nu) > 65$ GeV		
Cut-6	$P_T^{frac} < 0.15$		
Cut-7	280 GeV $< P_T^{axial} < 470$ GeV	220 GeV $< P_T^{axial} < 380$ GeV	140 GeV $< P_T^{axial} < 240$ GeV
Cut-8	$H_T < 440$ GeV	$H_T < 370$ GeV	$H_T < 250$ GeV

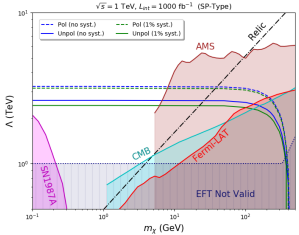


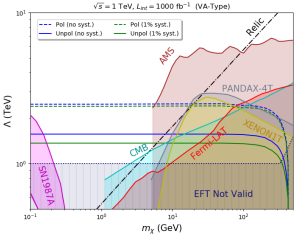
Operator types	Signal significance for $\mathcal{L}_{\rm int} = 1000\,{\rm fb}^{-1}$					
	Unpolarized beams			Polarized Beam		
	BP-1	BP-2	BP-3	BP-1	BP-2	BP-3
SP-type	4.7 (3.3)	1.5 (1.0)	0.3 (0.2)	10.3 (9.1)	3.6 (3.1)	0.8 (0.6)
VA-type	0.4 (0.2)	0.3 (0.1)	0.1 (0.1)	0.2 (0.1)	0.1 (0.1)	0.1 (0.04)
TAT-type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

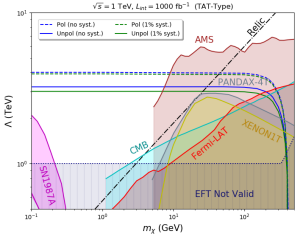
- (20-25)% signal events retained.
- More than 96% neutrino-pair background rejected.
- 99% of the $\ell\nu jj$ events are rejected.

Sensitivities

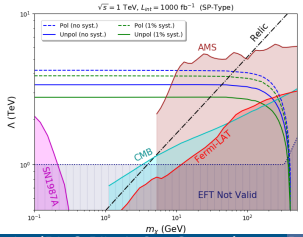
Leptonic Channel:

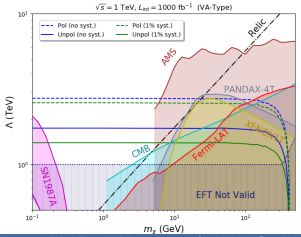


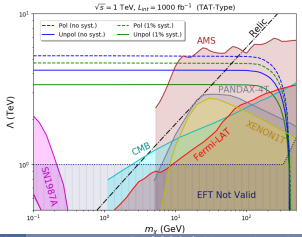




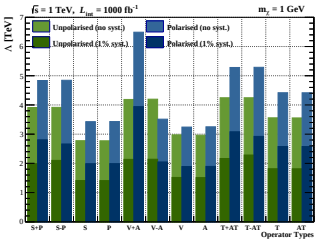
Hadronic Channel:

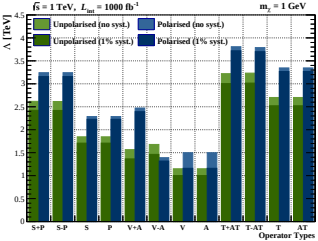


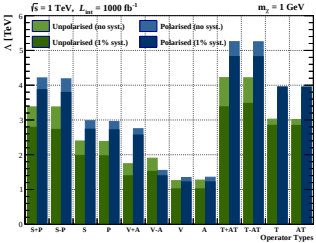




Conclusion







- 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.

Thank You!