Searching for dark matter in the mono-Z channel at high energy e^+e^- colliders

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Work in progress

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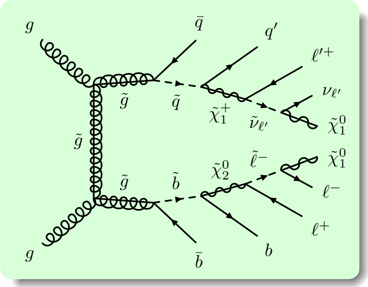
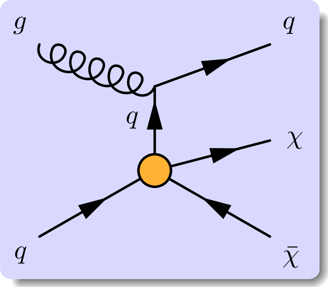
Chinese Academy of Sciences

Dark matter (DM) searches at colliders





Social dark matter

Accompanied by other new particles

Complicated decay chains

Decay products of other particles

Various final states

(jets + leptons + $\not\!\!E_\mathrm{T}$, ...)

Maverick dark matter

DM particle is the only new particle reachable at the collision energy

Direct production

Mono-X + $\not\!\!E$ final states

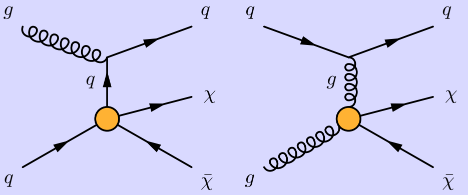
(monojet, mono-γ, mono-W/Z, ...)

(From Rocky Kolb's talk)

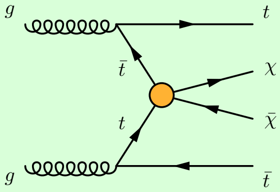
Studies on DM direct productions at colliders

Birkedal, Matchev and Perelstein, arXiv:hep-ph/0403004 (monophoton, e^+e^- colliders).
Q. -H. Cao, C. -R. Chen, C. S. Li and H. Zhang, arXiv:0912.4511 (monojet, monophoton, mono-Higgs, hadron colliders).
Beltran, Hooper, Kolb, Krusberg and Tait, arXiv:1002.4137 (monojet, hadron colliders).
Goodman, Ibe, Rajaraman, Shepherd, Tait and H. -B. Yu, arXiv:1005.1286 (monojet, hadron colliders).
Y. Bai, Fox and Harnik, arXiv:1005.3797 (monojet, hadron colliders).
Fox, Harnik, Kopp and Y. Tsai, arXiv:1103.0240 (monophoton, e^+e^- colliders).
Kamenik and Zupan, arXiv:1107.0623 (mono-t, hadron colliders).
J. Wang, C. S. Li, D. Y. Shao and H. Zhang, arXiv:1107.2048 (monophoton, hadron colliders).
Rajaraman, Shepherd, Tait and Wijangco, arXiv:1108.1196 (monojet, hadron colliders).
Fox, Harnik, Kopp and Y. Tsai, arXiv:1109.4398 (monojet, monophoton, hadron colliders).
K. Cheung, P. -Y. Tseng, Y. -L. S. Tsai and T. -C. Yuan, arXiv:1201.3402 (monojet, hadron colliders).
H. An, X. Ji and L. -T. Wang, arXiv:1202.2894 (monojet, hadron colliders).
Bartels, Berggren and List, arXiv:1206.6639 (monophoton, e^+e^- colliders).
Y. Bai and Tait, arXiv:1208.4361 [hep-ph] (mono-W, hadron colliders).
Bell, Dent, Galea, Jacques, Krauss and Weiler, arXiv:1209.0231 (mono-Z, hadron colliders).
F. P. Huang, C. S. Li, J. Wang and D. Y. Shao, arXiv:1210.0195 (monophoton, hadron colliders).
Dreiner, Huck, Kramer, Schmeier and Tattersall, arXiv:1211.2254 (monophoton, e^+e^- colliders).
Chae and Perelstein, arXiv:1211.4008 (monophoton, e^+e^- colliders).
Fox and Williams, arXiv:1211.6390 (monojet, hadron colliders).
Carpenter, Nelson, Shimmin, Tait and Whiteson, arXiv:1212.3352 (mono-Z, hadron colliders).
R. Ding, Y. Liao, J. -Y. Liu and K. Wang, arXiv:1302.4034 (monojet, hadron colliders).
T. Lin, E. W. Kolb and L. -T. Wang, arXiv:1303.6638 (mono-bjet, $b\bar{b}/t\bar{t}+\not{E}_{\mathrm{T}}$, hadron colliders).
Nelson, Carpenter, Cotta, Johnstone and Whiteson, arXiv:1307.5064 [hep-ph] (monophoton, hadron colliders).
N. Zhou, Berge, L. Wang, Whiteson and Tait, arXiv:1307.5327 (monojet, hadron colliders).
Z. -H. Yu, Q. -S. Yan and P. -F. Yin, arXiv:1307.5740 (monophoton, e^+e^- colliders).
Artoni, T. Lin, Penning, Sciolla and Venturini, arXiv:1307.7834 (mono-bjet, $b\bar{b}/t\bar{t}+\not{E}_{\mathrm{T}}$, hadron colliders).
H. An, L. -T. Wang and H. Zhang, arXiv:1308.0592 (monojet, $jj+\not{E}_{\mathrm{T}}$, hadron colliders).
Petrov and Shepherd, arXiv:1311.1511 (mono-Higgs, hadron colliders).
Bell, Y. Cai and Medina, arXiv:1311.6169 ($jj/\ell\ell+\not{E}_{\mathrm{T}}$, hadron colliders).
Carpenter, DiFranzo, Mulhearn, Shimmin, Tulin and Whiteson, arXiv:1312.2592 (mono-Higgs, hadron colliders).
... ...

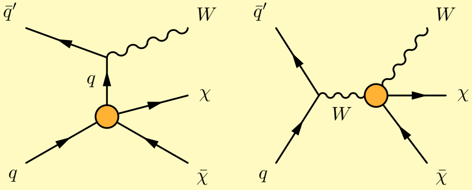
DM direct productions at colliders



Monojet + $\not{E}_T$

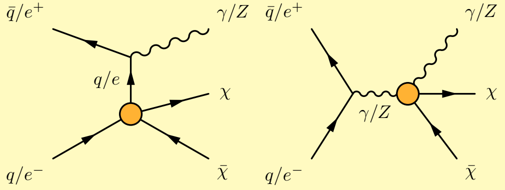


$t\bar{t} + \not{E}_T$

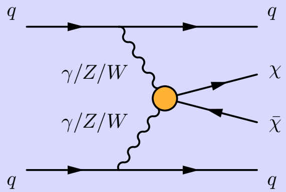


Mono-W + $\not{E}_T$

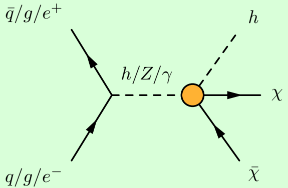
DM direct productions at colliders



Monophoton/mono-$Z + \not{E}$



$jj + \not{E}_{\mathrm{T}}$



Mono-Higgs $+ \not{E}$

Mono-Z signature: DM couplings to $ZZ/Z\gamma$

The mono-Z channel at high energy e^+e^- collider can be sensitive to **the DM coupling to $ZZ/Z\gamma$.**

Assuming the DM particle χ is a Dirac fermion, we consider the following effective operators:

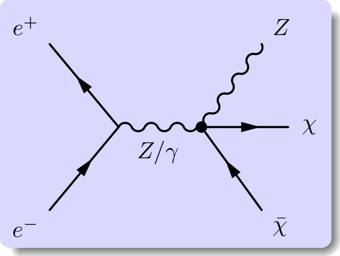
$$\mathcal{O}_{\mathrm{F1}} = \frac{1}{\Lambda_1^3}\bar{\chi}\chi B_{\mu\nu}B^{\mu\nu} + \frac{1}{\Lambda_2^3}\bar{\chi}\chi W^a_{\mu\nu}W^{a\mu\nu}$$

$$\supset \bar{\chi}\chi(G_{\mathrm{ZZ}}Z_{\mu\nu}Z^{\mu\nu} + G_{\mathrm{AZ}}A_{\mu\nu}Z^{\mu\nu})$$

$$\mathcal{O}_{\mathrm{F2}} = \frac{1}{\Lambda_1^3}\bar{\chi}i\gamma_5\chi B_{\mu\nu}\tilde{B}^{\mu\nu} + \frac{1}{\Lambda_2^3}\bar{\chi}i\gamma_5\chi W^a_{\mu\nu}\tilde{W}^{a\mu\nu}$$

$$\supset \bar{\chi}i\gamma_5\chi(G_{\mathrm{ZZ}}Z_{\mu\nu}\tilde{Z}^{\mu\nu} + G_{\mathrm{AZ}}A_{\mu\nu}\tilde{Z}^{\mu\nu})$$

$$\mathcal{O}_{\mathrm{FH}} = \frac{1}{\Lambda^3}\bar{\chi}\chi(D_\mu H)^\dagger D_\mu H \rightarrow \frac{m_Z^2}{2\Lambda^3}\bar{\chi}\chi Z_\mu Z^\mu$$

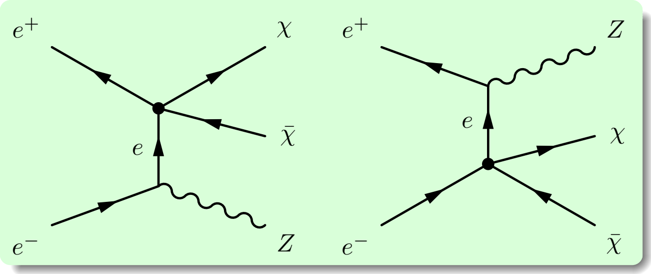


$$G_{\mathrm{ZZ}} \equiv \frac{\sin^2\theta_W}{\Lambda_1^3} + \frac{\cos^2\theta_W}{\Lambda_2^3}$$

$$G_{\mathrm{AZ}} \equiv 2\sin\theta_W\cos\theta_W\left(\frac{1}{\Lambda_2^3} - \frac{1}{\Lambda_1^3}\right)$$

Mono-Z signature: DM couplings to e^+e^-

This channel can also be sensitive to **the DM coupling to e^+e^-.**



We consider the following effective operators:

$$\mathcal{O}_{\mathrm{FP}} = \frac{1}{\Lambda^2}\bar{\chi}\gamma_5\chi\bar{e}\gamma_5 e, \quad \mathcal{O}_{\mathrm{FA}} = \frac{1}{\Lambda^2}\bar{\chi}\gamma^\mu\gamma_5\chi\bar{e}\gamma_\mu\gamma_5 e$$

MC simulation

Simulation tools: `FeynRules` → `MadGraph` → `PYTHIA` → `PGS`

SiD/ILD-like detector:

ECAL energy resolution $\frac{\Delta E}{E} = \frac{17\%}{\sqrt{E/\mathrm{GeV}}} \oplus 1\%$

HCAL energy resolution $\frac{\Delta E}{E} = \frac{30\%}{\sqrt{E/\mathrm{GeV}}}$

Collision energies of future e^+e^- colliders:

$\sqrt{s} = 250\,\mathrm{GeV}$: "Higgs factory" (CEPC/TLEP, ILC)

$\sqrt{s} = 500\,\mathrm{GeV}$: typical ILC

$\sqrt{s} = 1\,\mathrm{TeV}$: upgraded ILC

Lepton channel: $Z \to \ell^+\ell^-$ $(\ell = e, \mu)$

SM backgrounds: $e^+e^- \to \ell^+\ell^-\bar{\nu}\nu$, $e^+e^- \to \tau^+\tau^-$, $e^+e^- \to \tau^+\tau^-\bar{\nu}\nu$

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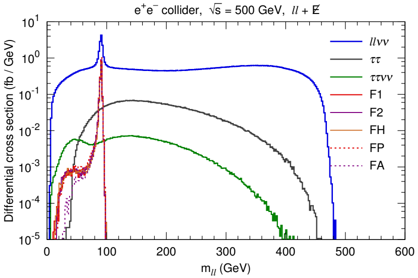
Reconstructing the Z boson: require only 2 leptons (e's or μ's) with $p_T > 10$ GeV and $|\eta| < 3$, and they are opposite sign and same flavor;
no any other particle;



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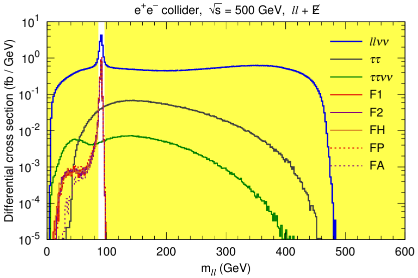

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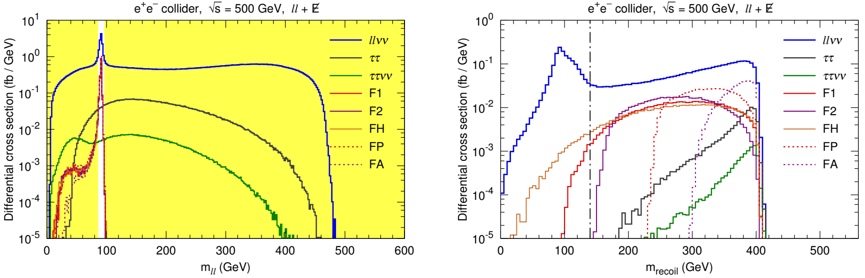
Reconstructing the recoil mass: $m_{\text{recoil}} = \sqrt{(p_{e^+} + p_{e^-} - p_{\ell_1} - p_{\ell_2})^2}$;



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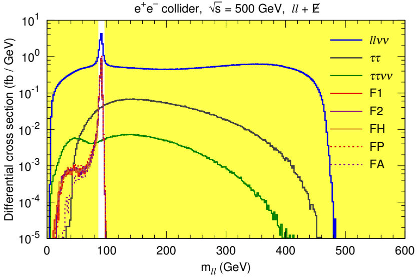
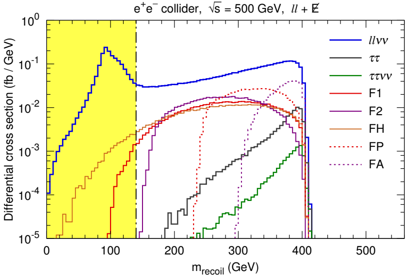
Reconstructing the recoil mass: $m_{\text{recoil}} = \sqrt{(p_{e^+} + p_{e^-} - p_{\ell_1} - p_{\ell_2})^2}$; veto events with $m_{\text{recoil}} < 140$ GeV.





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Cross sections σ and signal significances $\mathcal{S}$ after each cut

($\sqrt{s} = 500$ GeV, with an integrated luminosity of 100 fb^{-1})

	$\ell^+\ell^-\bar{\nu}\nu$	$\tau^+\tau^-$	$\tau^+\tau^-\bar{\nu}\nu$	$\mathcal{O}_{\mathrm{F1}}$		$\mathcal{O}_{\mathrm{F2}}$		$\mathcal{O}_{\mathrm{FH}}$		$\mathcal{O}_{\mathrm{FP}}$		$\mathcal{O}_{\mathrm{FA}}$	
	σ	σ	σ	σ	$\mathcal{S}$	σ	$\mathcal{S}$	σ	$\mathcal{S}$	σ	$\mathcal{S}$	σ	$\mathcal{S}$
Cut 1	**306**	**20.4**	**2.85**	2.65	1.46	2.94	1.61	2.47	1.36	3.24	1.78	2.86	1.57
Cut 2	235	11.8	1.29	2.52	1.60	2.82	1.78	2.39	1.51	3.19	2.01	2.19	1.38
Cut 3	23.9	0.410	0.0495	2.41	4.67	2.70	5.18	2.29	4.44	3.06	5.84	2.09	4.07
Cut 4	16.0	0.410	0.0495	2.39	5.51	2.70	6.16	2.19	5.08	3.06	6.92	2.09	4.86
Cut 5	**12.1**	**0.410**	**0.0471**	2.19	5.69	2.42	6.24	2.11	5.50	2.95	7.47	2.01	5.25

(σ in fb, $\mathcal{S} = S/\sqrt{S+B}$)

Hadron channel: $Z \to jj$

SM backgrounds: $e^+e^- \to jj\bar{\nu}\nu$, $e^+e^- \to jj\ell\nu$, $e^+e^- \to t\bar{t}$

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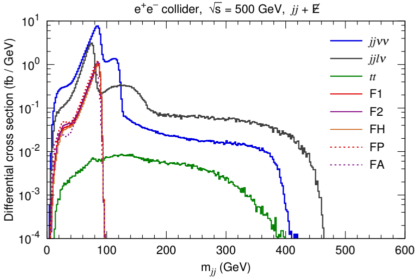

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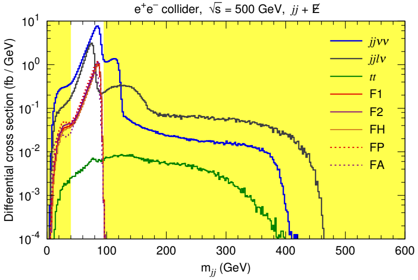

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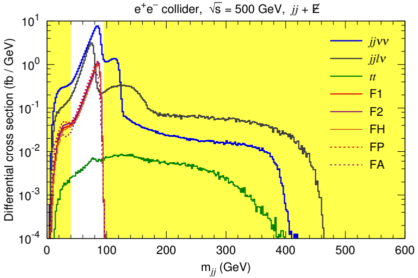

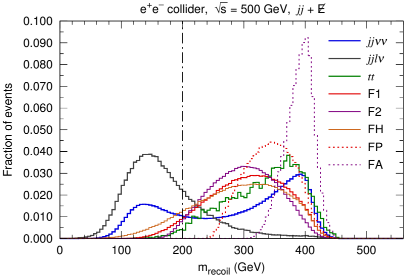

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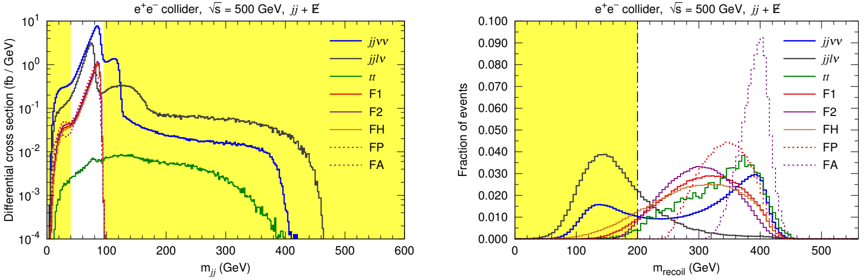
Reconstructing the recoil mass: $m_{\mathrm{recoil}} = \sqrt{(p_{e^+} + p_{e^-} - p_{j_1} - p_{j_2})^2}$; veto events with $m_{\mathrm{recoil}} <$ 200 GeV.



Hadron channel: $Z \to jj$

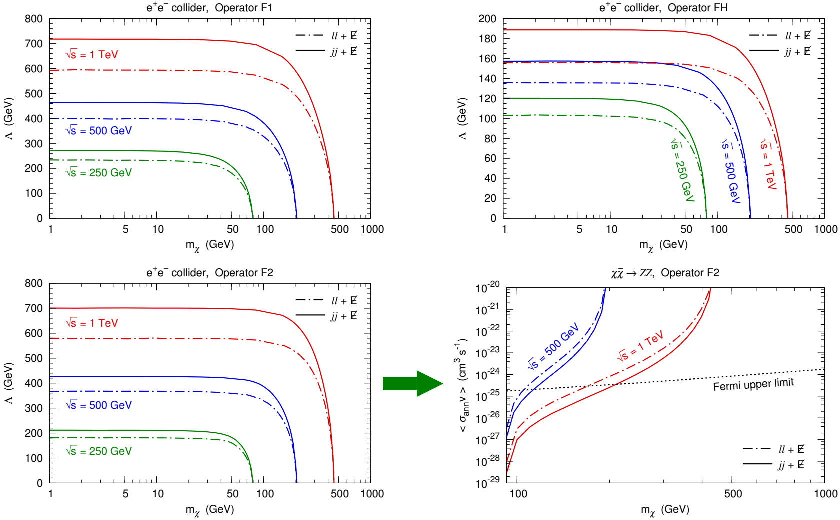
Cross sections σ and signal significances $\mathcal{S}$ after each cut

($\sqrt{s} = 500$ GeV, with an integrated luminosity of 100 fb^{-1})

	$jj\nu\bar{\nu}$	$jj\ell\nu$	$t\bar{t}$	$\mathcal{O}_{\rm F1}$		$\mathcal{O}_{\rm F2}$		$\mathcal{O}_{\rm FH}$		$\mathcal{O}_{\rm FP}$		$\mathcal{O}_{\rm FA}$	
	σ	σ	σ	σ	$\mathcal{S}$	σ	$\mathcal{S}$	σ	$\mathcal{S}$	σ	$\mathcal{S}$	σ	$\mathcal{S}$
Cut 1	**245**	**131**	**1.74**	18.9	9.47	20.9	10.4	17.8	8.94	22.1	11.1	18.4	9.24
Cut 2	207	93.2	1.56	18.0	10.0	20.0	11.2	17.2	9.64	21.8	12.1	13.9	7.84
Cut 3	160	56.6	0.270	17.2	11.2	19.2	12.5	16.6	10.8	20.7	13.5	13.3	8.76
Cut 4	115	14.9	0.264	16.3	13.4	18.7	15.3	14.6	12.1	20.7	16.9	13.3	11.1
Cut 5	**92.6**	**2.91**	**0.253**	15.1	14.3	17.1	16.1	14.1	13.5	20.1	18.7	12.9	12.3

(σ in fb, $\mathcal{S} = S/\sqrt{S+B}$)

3σ sensitivity: DM couplings to $ZZ/Z\gamma$



(with an integrated luminosity of 1000 fb^{-1}, assuming $\Lambda = \Lambda_1 = \Lambda_2$ for $\mathcal{O}_{F1}$ and $\mathcal{O}_{F2}$)

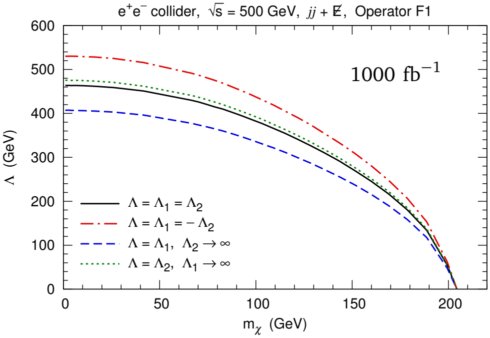
3σ sensitivity affected by the Λ_1-Λ_2 relation

$\chi\chi ZZ$ coupling:

$$G_{ZZ} = \frac{\sin^2\theta_W}{\Lambda_1^3} + \frac{\cos^2\theta_W}{\Lambda_2^3}$$

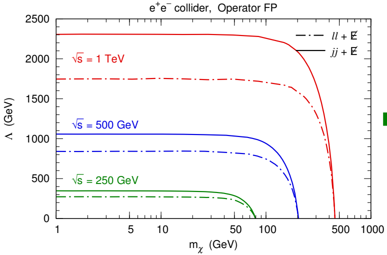
$\chi\chi\gamma Z$ coupling:

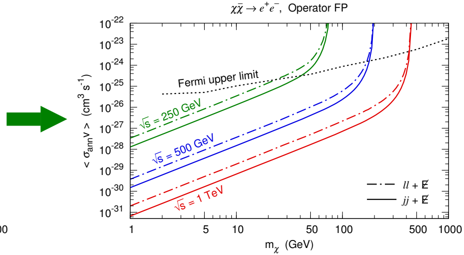
$$G_{AZ} = 2\sin\theta_W\cos\theta_W\left(\frac{1}{\Lambda_2^3} - \frac{1}{\Lambda_1^3}\right)$$

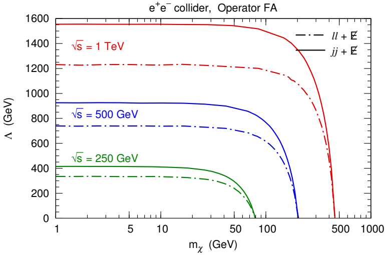


$\Lambda = \Lambda_1 = \Lambda_2$: only the $\chi\chi ZZ$ coupling contributes.
$\Lambda = \Lambda_1 = -\Lambda_2$: the $\chi\chi\gamma Z$ coupling is dominant.
$\Lambda = \Lambda_1,\ \Lambda_2 \to \infty$: the $\chi\chi\gamma Z$ coupling is dominant.
$\Lambda = \Lambda_2,\ \Lambda_1 \to \infty$: the $\chi\chi ZZ$ and the $\chi\chi\gamma Z$ couplings are comparable.

3σ sensitivity: DM couplings to e^+e^-

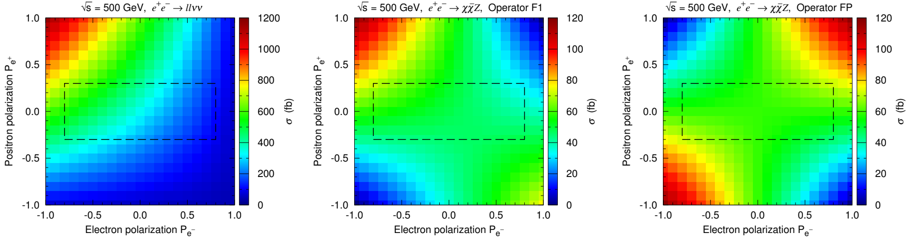






(with an integrated luminosity of 1000 fb^{-1}; Fermi upper limits come from arXiv:1310.0828)

Cross sections with polarized beams



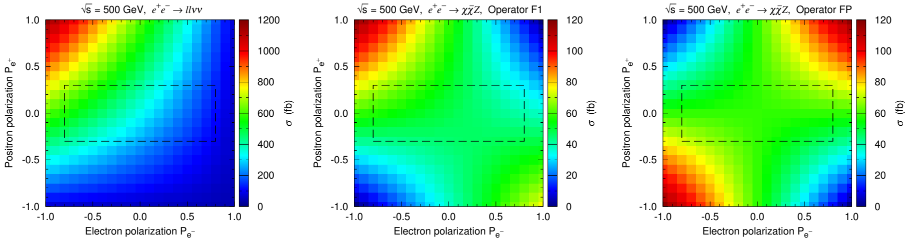
($\ell\ell\bar{\nu}\nu$, $jj\bar{\nu}\nu$, $jj\ell\nu$ are similar) ($\mathcal{O}_{\rm F1}$, $\mathcal{O}_{\rm F2}$, $\mathcal{O}_{\rm FH}$, $\mathcal{O}_{\rm FA}$ are similar) ($\mathcal{O}_{\rm FP}$)

- $W^\pm$ only couples to left-handed e^- (right-handed e^+).
- $e^\pm$ couples to Z^0 via $\frac{g_2}{2\cos\theta_W}(g_L\bar{e}_L\gamma^\mu e_L + g_R\bar{e}_R\gamma^\mu e_R)Z_\mu$.

  $g_L = -1 + 2\sin^2\theta_W \simeq -0.56$, $g_R = 2\sin^2\theta_W \simeq 0.44$, $g_L^2/g_R^2 \simeq 1.56$.

  The left-handed e^- (right-handed e^+) coupling to Z^0 is stronger.

Cross sections with polarized beams



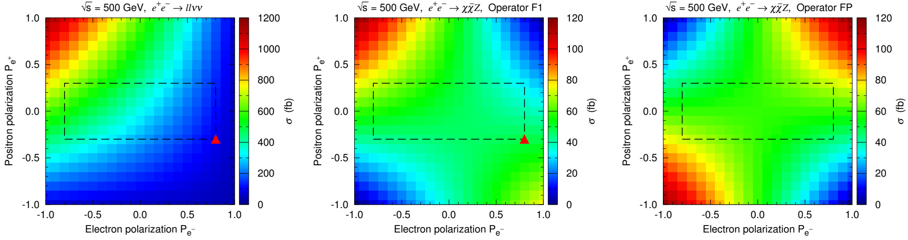
($\ell\ell\bar{\nu}\nu$, $jj\bar{\nu}\nu$, $jj\ell\nu$ are similar) ($\mathcal{O}_{\rm F1}$, $\mathcal{O}_{\rm F2}$, $\mathcal{O}_{\rm FH}$, $\mathcal{O}_{\rm FA}$ are similar) ($\mathcal{O}_{\rm FP}$)

The dashed box indicates the polarization ranges achievable at the ILC:

$$-0.8 \le P_{e^-} \le +0.8, \quad -0.3 \le P_{e^+} \le +0.3.$$

In order to obtain the maximal signal significance,

Cross sections with polarized beams



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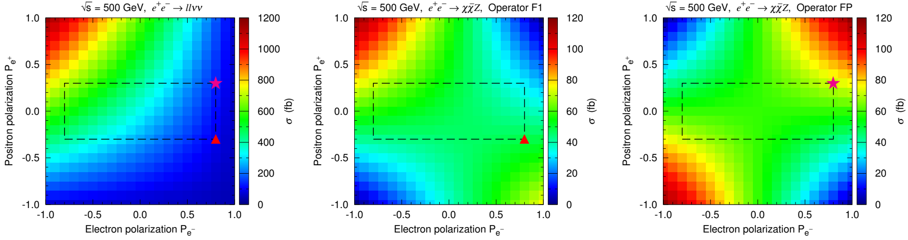

$(\ell\ell\bar{\nu}\nu,\ jj\bar{\nu}\nu,\ jj\ell\nu$ are similar) $(\mathcal{O}_{\rm F1},\ \mathcal{O}_{\rm F2},\ \mathcal{O}_{\rm FH},\ \mathcal{O}_{\rm FA}$ are similar) $(\mathcal{O}_{\rm FP})$

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Sensitivity improvements

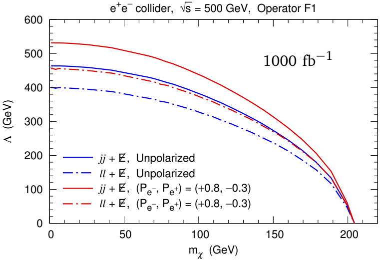
Signal significances without and **with** polarized beams for the benchmark points at $\sqrt{s} = 500$ GeV $(100\ \text{fb}^{-1})$:

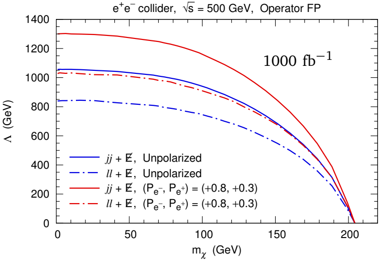
Lepton channel $\ell^+\ell^- + \not{E}$

	$\mathcal{S}_{\text{unpol}}$	$\mathcal{S}_{\text{pol}}$	$\mathcal{S}_{\text{pol}}/\mathcal{S}_{\text{unpol}}$
$\mathcal{O}_{\text{F1}}$	5.69	10.1	**1.78**
$\mathcal{O}_{\text{F2}}$	6.24	10.9	**1.75**
$\mathcal{O}_{\text{FH}}$	5.50	9.70	**1.76**
$\mathcal{O}_{\text{FP}}$	7.47	13.4	**1.79**
$\mathcal{O}_{\text{FA}}$	5.25	9.29	**1.77**

Hadron channel $jj + \not{E}$

	$\mathcal{S}_{\text{unpol}}$	$\mathcal{S}_{\text{pol}}$	$\mathcal{S}_{\text{pol}}/\mathcal{S}_{\text{unpol}}$
$\mathcal{O}_{\text{F1}}$	14.3	26.0	**1.82**
$\mathcal{O}_{\text{F2}}$	16.1	28.6	**1.78**
$\mathcal{O}_{\text{FH}}$	13.5	24.8	**1.84**
$\mathcal{O}_{\text{FP}}$	18.7	34.4	**1.84**
$\mathcal{O}_{\text{FA}}$	12.3	23.0	**1.87**





Conclusions and discussions

1. In addition to DM direct and indirect detection, DM searches at colliders provide **an independent and complementary way** to explore the microscopic nature of DM particles.
2. The mono-Z searching channel at e^+e^- colliders is sensitive to **the DM couplings to $ZZ/Z\gamma$ and to e^+e^-**.
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1. In addition to DM direct and indirect detection, DM searches at colliders provide **an independent and complementary way** to explore the microscopic nature of DM particles.
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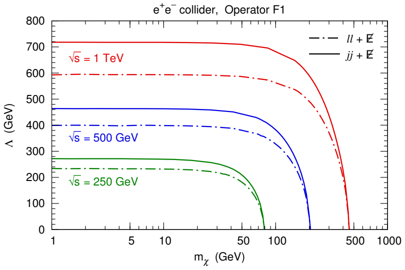
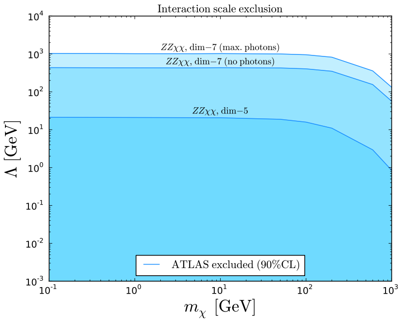
Thanks for your attentions!

Backup slides

Mono-Z: e^+e^- colliders vs. LHC



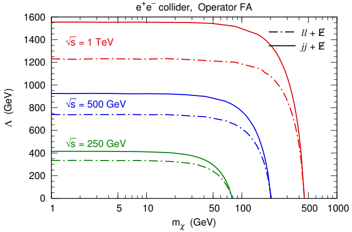
This work



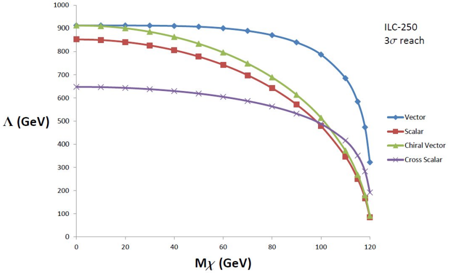
LHC, $\sqrt{s} = 7$ TeV, 4.6 fb^{-1}

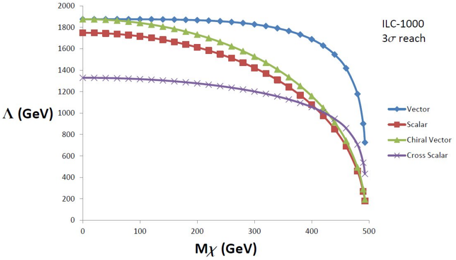
[Carpenter, Nelson, Shimmin, Tait and Whiteson, arXiv:1212.3352]

DM couplings to e^+e^-: mono-Z vs. monophoton



⇐ This work





[Chae and Perelstein, arXiv:1211.4008]