Detecting interactions between dark matter and electroweak gauge bosons at high energy e^+e^- colliders

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Based on
Phys. Rev. D **88**, 075015 [arXiv:1304.4128]
and arXiv:1404.xxxx

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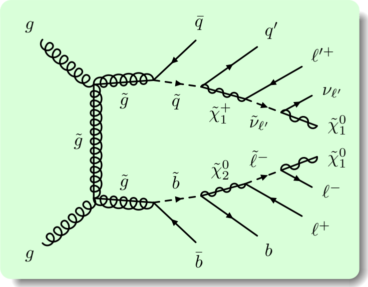
Institute of High Energy Physics
Chinese Academy of Sciences

Wuhan, April 21, 2013

Dark matter (DM) searches at colliders



Social dark matter

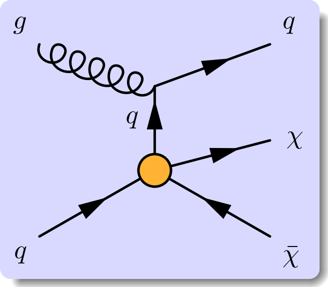
Accompanied by other new particles

Complicated decay chains

Decay products of other particles

Various final states

(jets + leptons + $\not{E}$, ...)



Maverick dark matter

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

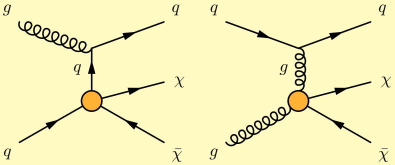
Direct production

Mono-X + $\not{E}$ final states

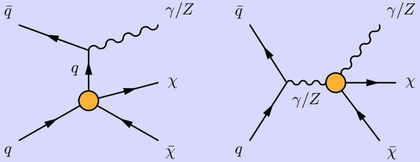
(monojet, mono-γ, mono-W/Z, ...)

(From Rocky Kolb's talk)

DM direct productions at hadron colliders



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



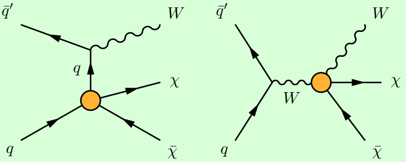
Monophoton/mono-Z $+ \not{E}_{\mathrm{T}}$

Sensitive to the DM couplings to

quarks, gluons

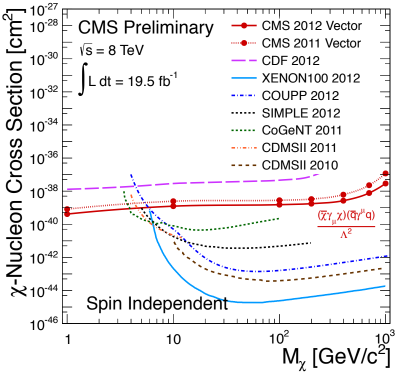
photons, Z bosons

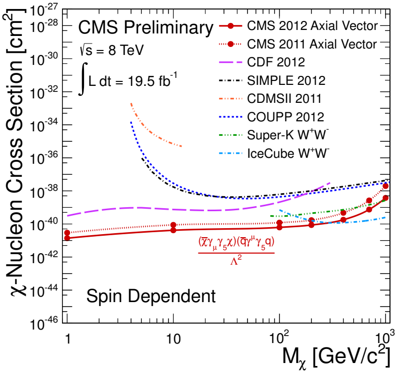
$W^{\pm}$ bosons



Mono-W $+ \not{E}_{\mathrm{T}}$

LHC vs. direct detection

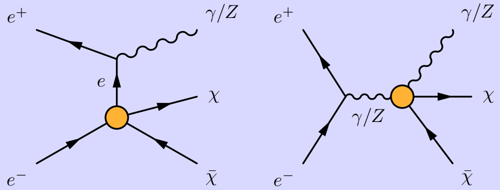




Constraints on DM-nucleon scattering cross section given by the CMS dark matter search in the monojet + $\not{E}_T$ final state with an integrated luminosity of $\sim 20\ \mathrm{fb}^{-1}$ at $\sqrt{s} = 8$ TeV.

[CMS PAS EXO-12-048]

DM direct productions at e^+e^- colliders



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

Sensitive to
the DM couplings to
electrons/positrons
photons
Z **bosons**

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

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

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

$\sqrt{s} = 1\,\text{TeV}$: upgraded **ILC** & initial **CLIC**

$\sqrt{s} = 3\,\text{TeV}$: ultimate **CLIC**

MC simulation

Simulation tools:

FeynRules (adding new particles & couplings)

MadGraph (parton-level calculation & sample generation)

PYTHIA (parton shower & hadronization)

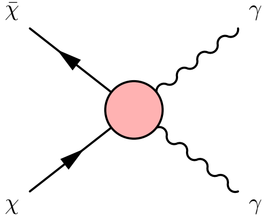
PGS (jet clustering & fast detector simulation)

SiD/ILD-like detector:

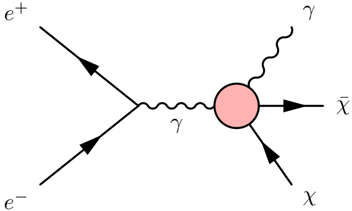
ECAL energy resolution $\frac{\Delta E}{E} = \frac{17\%}{\sqrt{E/\mathrm{GeV}}} \oplus 1\%$

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

DM-photon interaction



$\Leftrightarrow$



$\chi\bar{\chi} \to \gamma\gamma$

Indirect search

γ-ray line signature

$e^+e^- \to \chi\bar{\chi}\gamma$

Collider search

Monophoton signature ($\gamma + \not{E}$)

Effective operator approach

If DM particles couple to photons via exchanging some mediators which are **sufficiently heavy**, the DM-photon coupling can be approximately described by **effective contact operators**.

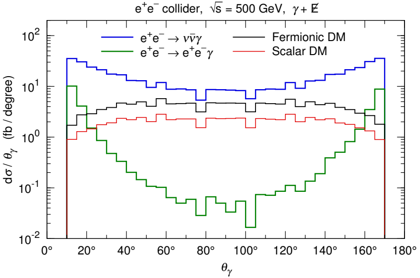
For Dirac fermionic DM, consider $\mathcal{O}_F = \frac{1}{\Lambda^3}\bar{\chi} i\gamma_5 \chi F_{\mu\nu}\tilde{F}^{\mu\nu}$**:**

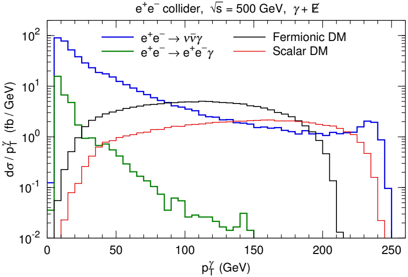
$$\langle \sigma_{\text{ann}} v \rangle_{\chi\bar{\chi}\to 2\gamma} \simeq \frac{4m_\chi^4}{\pi\Lambda^6}, \qquad \sigma(e^+e^- \to \chi\bar{\chi}\gamma) \sim \frac{s^2}{\Lambda^6}$$

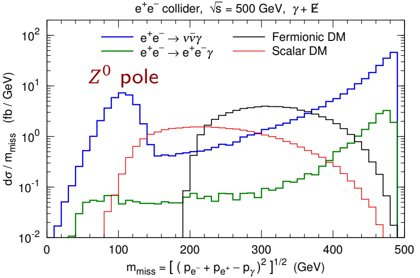
For complex scalar DM, consider $\mathcal{O}_S = \frac{1}{\Lambda^2}\chi^*\chi F_{\mu\nu}F^{\mu\nu}$**:**

$$\langle \sigma_{\text{ann}} v \rangle_{\chi\chi^*\to 2\gamma} \simeq \frac{2m_\chi^2}{\pi\Lambda^4}, \qquad \sigma(e^+e^- \to \chi\chi^*\gamma) \sim \frac{s}{\Lambda^4}$$

In the $\gamma + \not{E}$ searching channel, the main background is $e^+e^- \to \nu\bar{\nu}\gamma$.
Minor backgrounds are $e^+e^- \to e^+e^-\gamma$, $e^+e^- \to \tau^+\tau^-\gamma$, $\cdots$

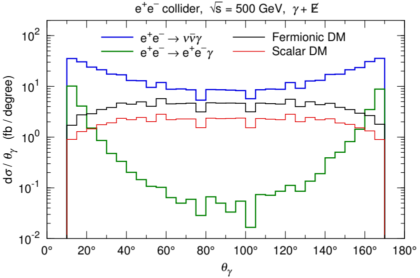


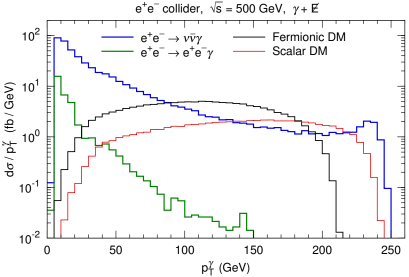


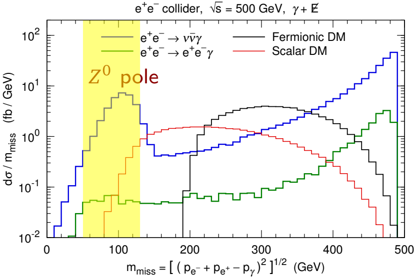


Cut 1 (pre-selection):
Require a photon with $E_\gamma > 10\,\mathrm{GeV}$ and $10^\circ < \theta_\gamma < 170^\circ$
Veto any other particle

Benchmark point: $\Lambda = 200\,\mathrm{GeV}$, $m_\chi = 100\,(50)\,\mathrm{GeV}$ for fermionic (scalar) DM







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Cut 2: Veto $50\,\mathrm{GeV} < m_{\mathrm{miss}} < 130\,\mathrm{GeV}$

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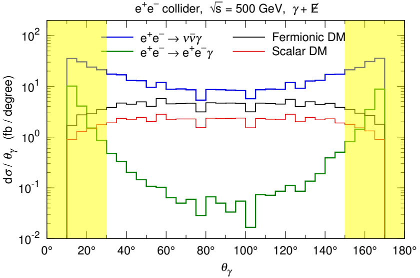

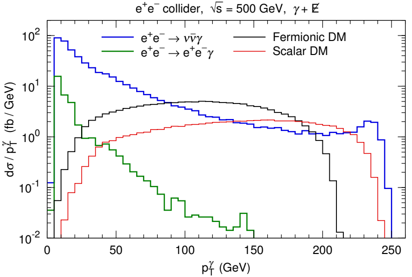

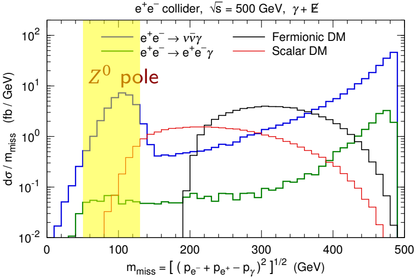

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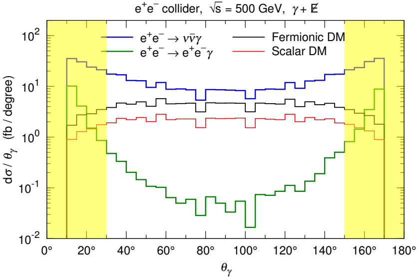

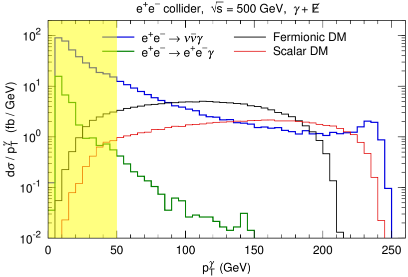

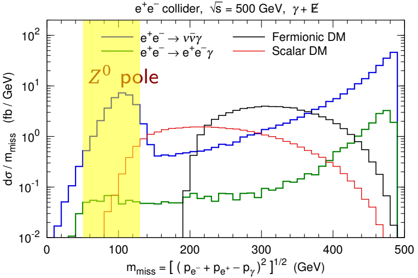

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Cut 3: Require $30^\circ < \theta_\gamma < 150^\circ$

Cut 4: Require $p_{\mathrm{T}}^{\gamma} > \sqrt{s}/10$

Benchmark point: $\Lambda = 200\,\mathrm{GeV}$, $m_\chi = 100\,(50)\,\mathrm{GeV}$ for fermionic (scalar) DM

Cross sections and signal significances after each cut

	$\nu\bar{\nu}\gamma$	$e^+e^-\gamma$	Fermionic DM		Scalar DM	
	σ (fb)	σ (fb)	σ (fb)	$S/\sqrt{B}$	σ (fb)	$S/\sqrt{B}$
Cut 1	**2415.2**	**173.0**	646.8	12.7	321.4	6.3
Cut 2	2102.5	168.6	646.8	13.6	308.2	6.5
Cut 3	1161.1	16.8	538.0	15.7	255.9	7.5
Cut 4	**254.5**	**1.9**	520.7	32.5	253.9	15.8

Benchmark point: $\Lambda = 200\,\text{GeV}$, $m_\chi = 100\,(50)\,\text{GeV}$ for fermionic (scalar) DM

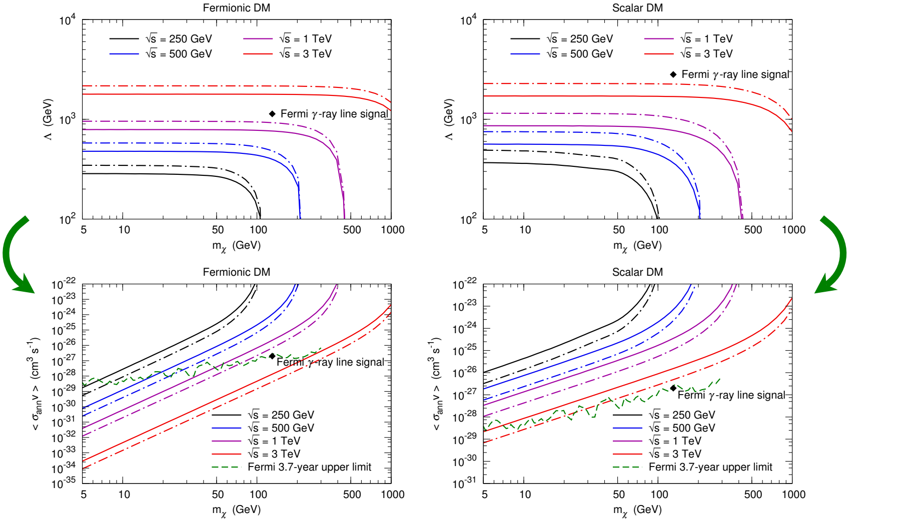
Most of the signal events remain

$e^+e^- \to \nu\bar{\nu}\gamma$ background: reduced by almost **an order of magnitude**

$e^+e^- \to e^+e^-\gamma$ background: only **one percent** survives

$(\sqrt{s} = 500\,\text{GeV},\ 1\,\text{fb}^{-1})$

3σ sensitivity

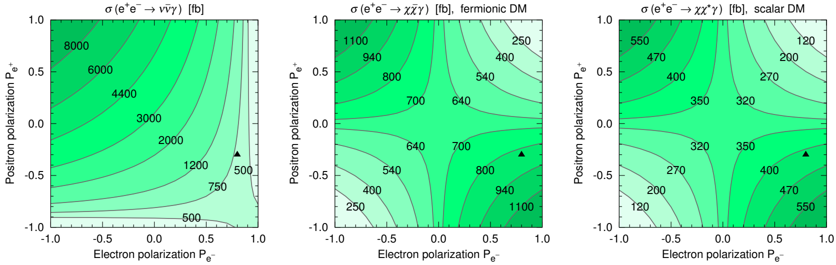


Solid lines: $100\,\text{fb}^{-1}$; dot-dashed lines: $1000\,\text{fb}^{-1}$ $(S/\sqrt{B} = 3)$

Beam polarization

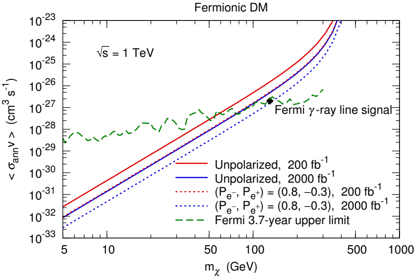
For a process at an e^+e^- collider with **polarized beams**,

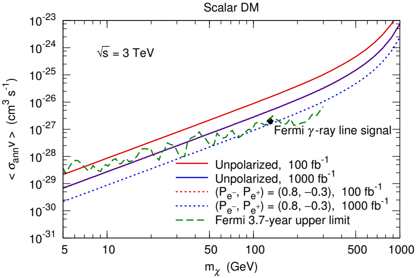
$$\sigma(P_{e^-},P_{e^+}) = \frac{1}{4}\Big[(1+P_{e^-})(1+P_{e^+})\sigma_{\mathrm{RR}} + (1-P_{e^-})(1-P_{e^+})\sigma_{\mathrm{LL}} + (1+P_{e^-})(1-P_{e^+})\sigma_{\mathrm{RL}} + (1-P_{e^-})(1+P_{e^+})\sigma_{\mathrm{LR}}\Big]$$



▲ $(P_{e^-},P_{e^+}) = (0.8,-0.3)$ **can be achieved at the ILC**

[ILC technical design report, Vol. 1, 1306.6327]





$(S/\sqrt{B} = 3)$

Using the **polarized beams** is roughly equivalent to **increasing** the integrated luminosity by **an order of magnitude**.

For fermionic DM (scalar DM), a data set of $2000\,\mathrm{fb}^{-1}$ $(1000\,\mathrm{fb}^{-1})$ would be just sufficient to test the potential Fermi γ-ray line signal at an e^+e^- collider with $\sqrt{s} = 1\,\mathrm{TeV}$ $(3\,\mathrm{TeV})$.

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:

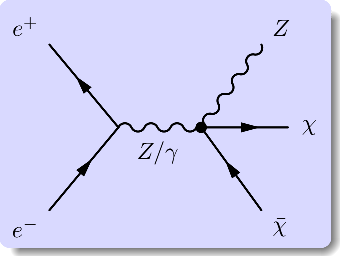
$$\mathcal{O}_{\text{F1}} = \frac{1}{\Lambda_1^3}\bar{\chi}\chi B_{\mu\nu}B^{\mu\nu} + \frac{1}{\Lambda_2^3}\bar{\chi}\chi W^a_{\mu\nu}W^{a\mu\nu}$$

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

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

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

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

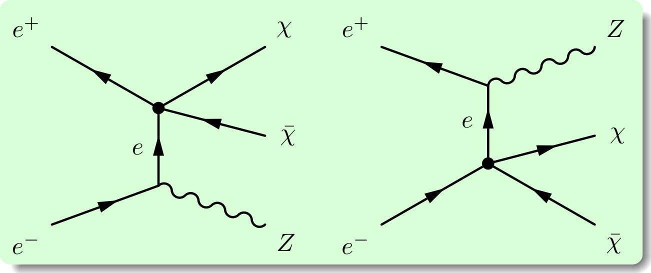


$$G_{\text{ZZ}} \equiv \frac{\sin^2\theta_W}{\Lambda_1^3} + \frac{\cos^2\theta_W}{\Lambda_2^3}$$

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

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:

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

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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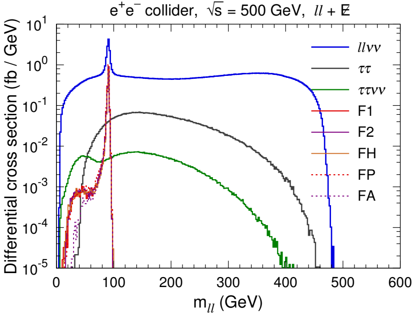
Reconstructing the Z boson: require only 2 leptons (e's or μ's) with $p_T > 10$ GeV and $|\eta| < 3$, and they are opposite sign and same flavor;

no any other particle;



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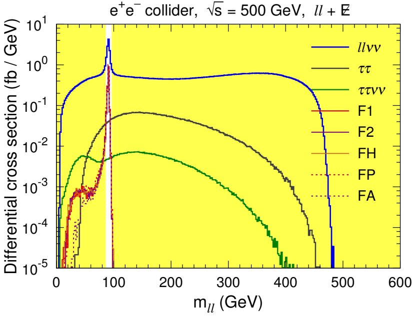

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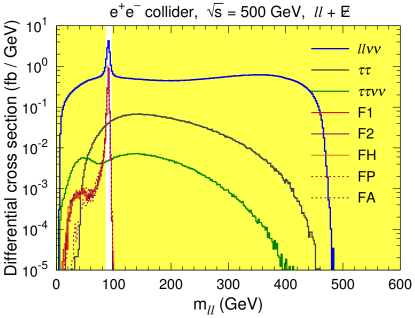
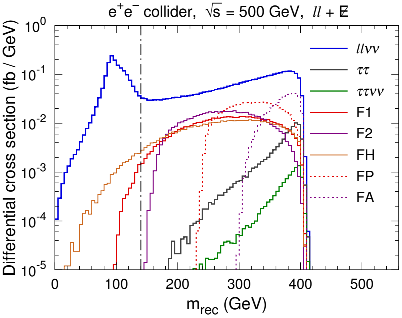
Reconstructing the recoil mass: $m_{\rm rec} = \sqrt{(p_{e^+} + p_{e^-} - p_{\ell_1} - p_{\ell_2})^2}$;





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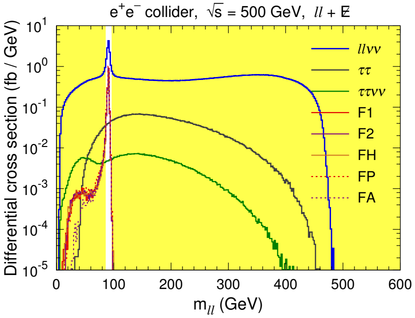
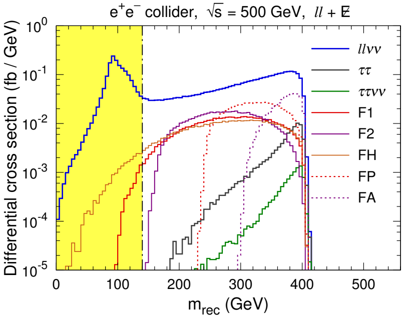
veto events with $m_{\rm rec} < 140$ GeV.





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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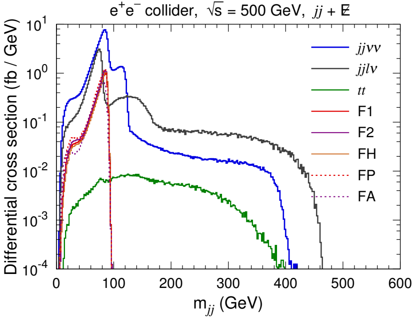

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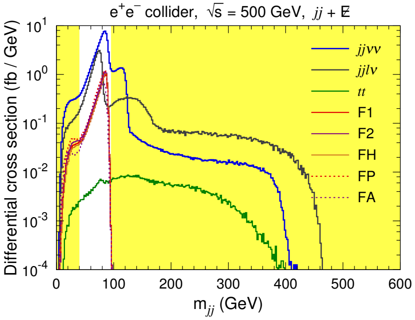

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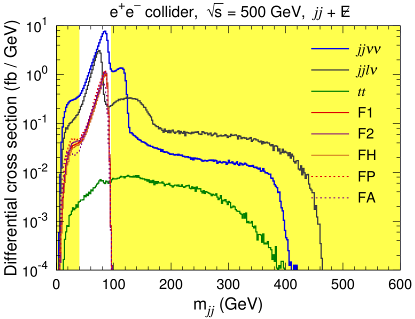
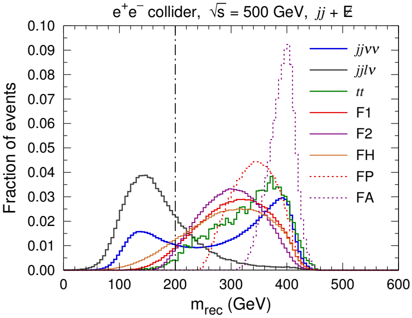


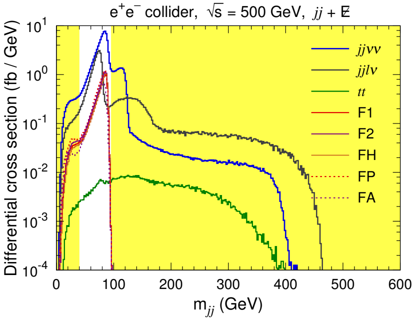


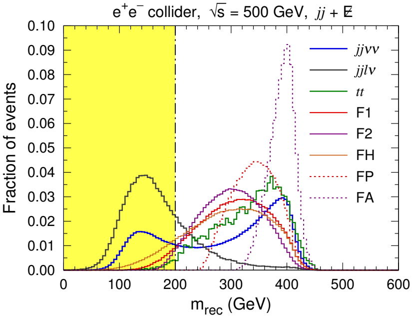
Hadron channel: $Z \to jj$

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

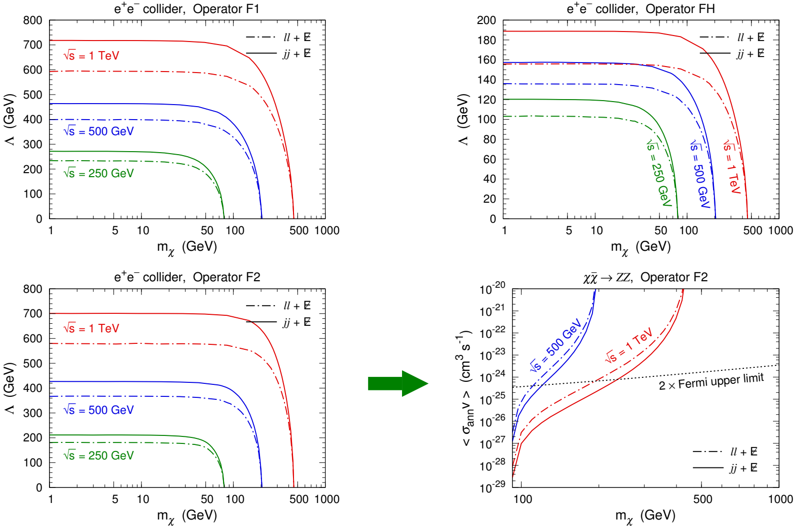
Reconstructing the Z boson: require only 2 jets with $p_{\mathrm{T}} > 10$ GeV and $|\eta| < 3$; **no any other particle;** require the invariant mass of the 2 jets satisfying 40 GeV $< m_{jj} <$ 95 GeV.

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



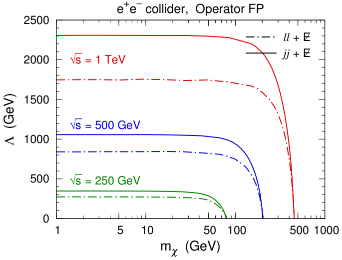


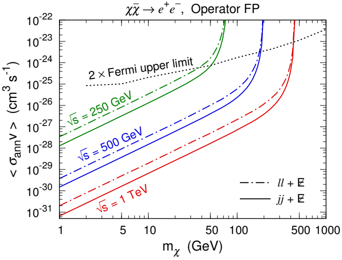
3σ sensitivity: DM couplings to $ZZ/Z\gamma$

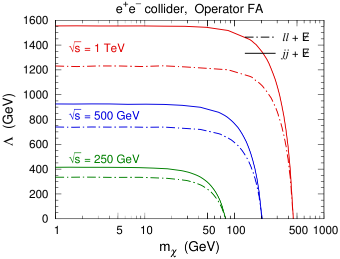


(with an integrated luminosity of 1000 fb^{-1}, assuming $\Lambda = \Lambda_1 = \Lambda_2$ for $\mathcal{O}_{\mathrm{F1}}$ and $\mathcal{O}_{\mathrm{F2}}$)

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

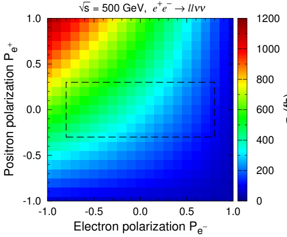




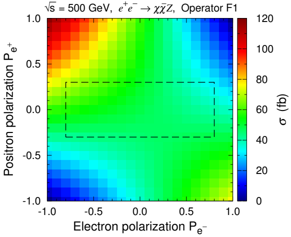


(with an integrated luminosity of 1000 fb^{-1}; Fermi upper limits come from arXiv:1310.0828)

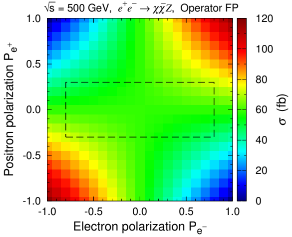
Cross sections with polarized beams



($\ell\ell\bar{\nu}\nu$, $jj\bar{\nu}\nu$, $jj\ell\nu$ are similar)



($\mathcal{O}_{\rm F1}$, $\mathcal{O}_{\rm F2}$, $\mathcal{O}_{\rm FH}$, $\mathcal{O}_{\rm FA}$ are similar)

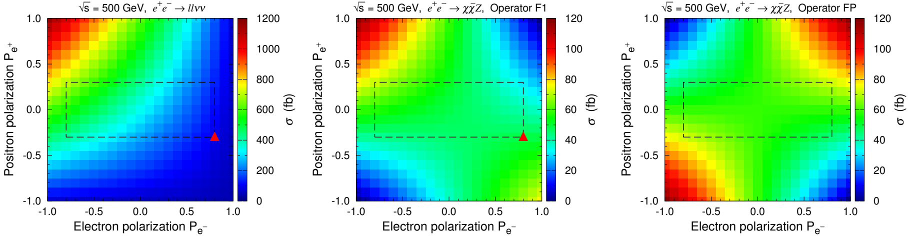


($\mathcal{O}_{\rm FP}$)

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

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

Cross sections with polarized beams



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

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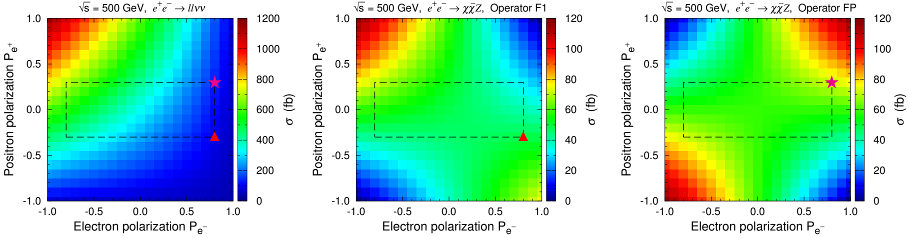
In order to obtain the maximal signal significance,

▲ $(P_{e^-}, P_{e^+}) = (+0.8, -0.3)$ is optimal for $\mathcal{O}_{\mathrm{F1}}$, $\mathcal{O}_{\mathrm{F2}}$, $\mathcal{O}_{\mathrm{FH}}$, $\mathcal{O}_{\mathrm{FA}}$;

Cross sections with polarized beams



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- ★ $(P_{e^-}, P_{e^+}) = (+0.8, +0.3)$ is optimal for $\mathcal{O}_{\rm FP}$.

Sensitivity improvements

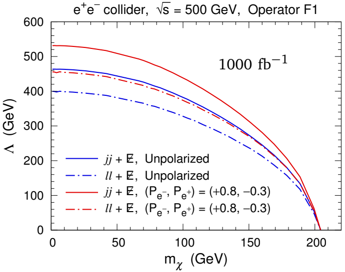
Signal significances without and with polarized beams for the benchmark points at $\sqrt{s} = 500$ GeV $(100\ \text{fb}^{-1})$:

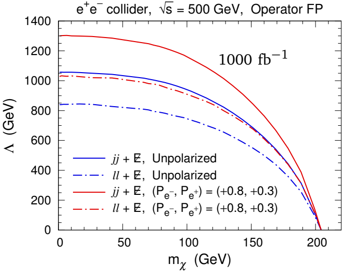
Lepton channel $\ell^+\ell^- + \not{E}$

	$\mathcal{S}_{\text{unpol}}$	$\mathcal{S}_{\text{pol}}$	$\mathcal{S}_{\text{pol}}/\mathcal{S}_{\text{unpol}}$
$\mathcal{O}_{\text{F1}}$	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 monophoton searching channel at e^+e^- colliders is sensitive to **the DM couplings to $\gamma\gamma$**.
3. The mono-Z searching channel at e^+e^- colliders is sensitive to **the DM couplings to $ZZ/Z\gamma$ and to e^+e^-**.
4. **Polarized beams** are helpful to improve the signal significance.

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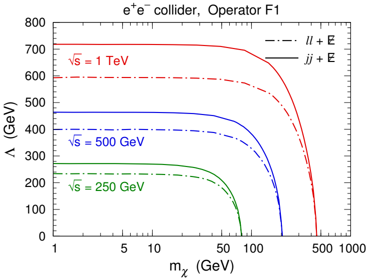
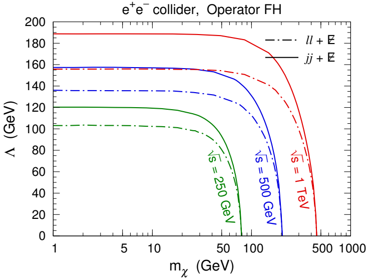
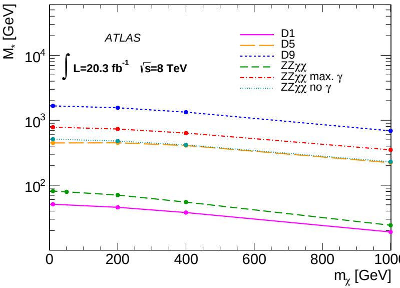
Thanks for your attentions!

Backup slides

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



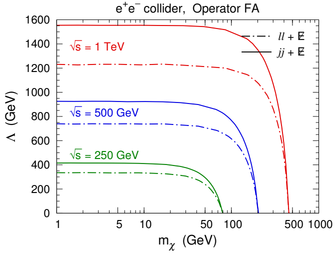




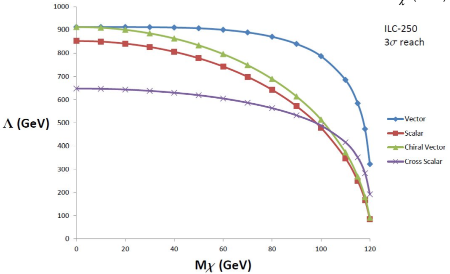
LHC, $\sqrt{s} = 8$ TeV, 20.3 fb^{-1}

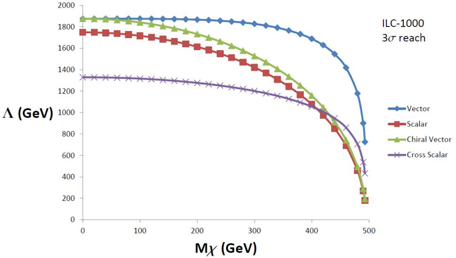
[ATLAS, arXiv:1404.0051]

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



⇐ This work





[Chae and Perelstein, arXiv:1211.4008]

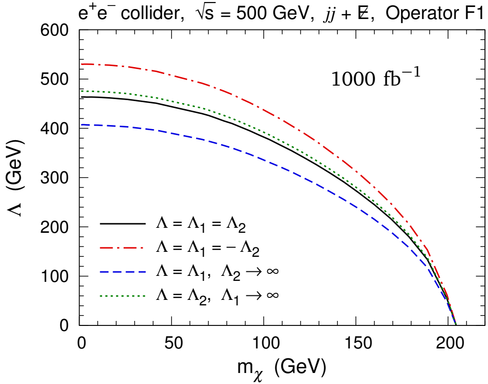
3σ sensitivity affected by the Λ_1-Λ_2 relation

$\chi\chi ZZ$ 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.

Chiral couplings in the standard model

- $W^\pm$ 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.

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

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: $Z \to jj$

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

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

	$jj\nu\bar{\nu}$	$jj\ell\nu$	$t\bar{t}$	$\mathcal{O}_{\text{F1}}$		$\mathcal{O}_{\text{F2}}$		$\mathcal{O}_{\text{FH}}$		$\mathcal{O}_{\text{FP}}$		$\mathcal{O}_{\text{FA}}$	
	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, $\mathcal{S} = S/\sqrt{S+B}$)