Dark matter searches at high energy colliders

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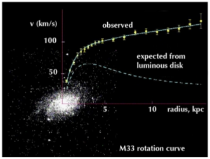
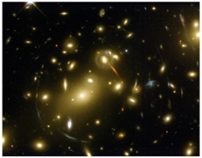
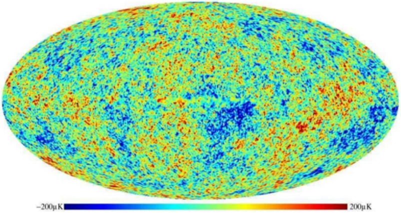
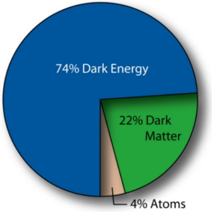
Dark matter (DM) in the Universe







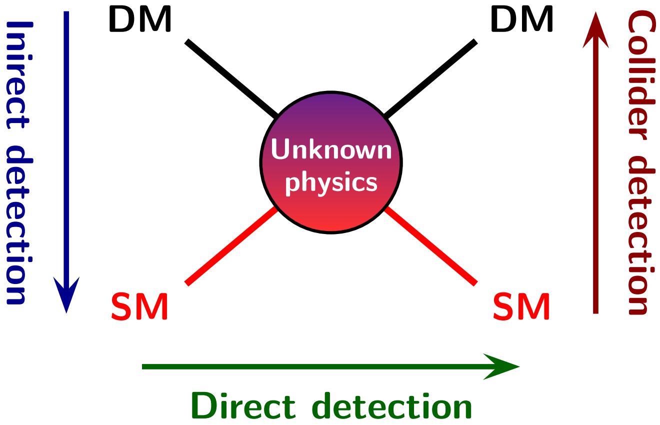


Dark matter exists at various scales in the Universe.

(galaxies, clusters, large scale structures, cosmological scale)

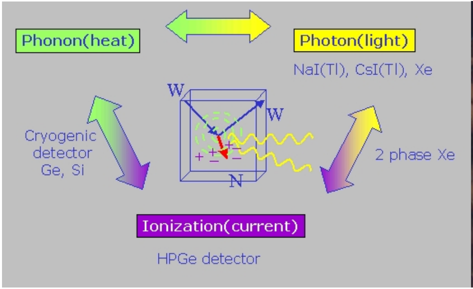
However, its microscopic property remains unknown.

Different kinds of DM detections

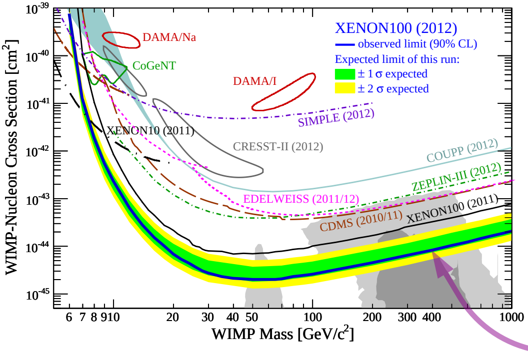


DM direct detection

Detect recoil signals of nuclei scattered by DM particles
(photons, phonons, ionization)
Work underground to reduce cosmic ray backgrounds

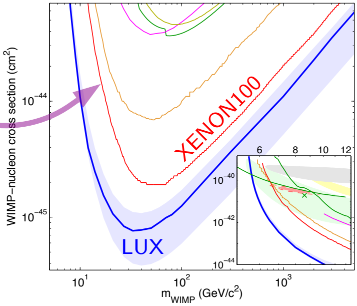


Direct detection results (spin independent)



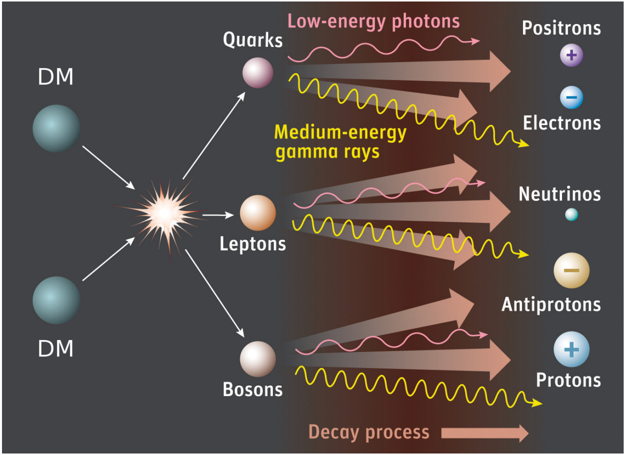
⇐ XENON100, arXiv:1207.5988

LUX, arXiv:1310.8214 ⇒

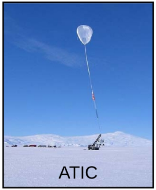


DM indirect detection

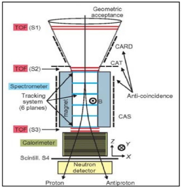
Search for products from DM annihilation or decay

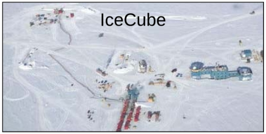


Indirect detection experiments

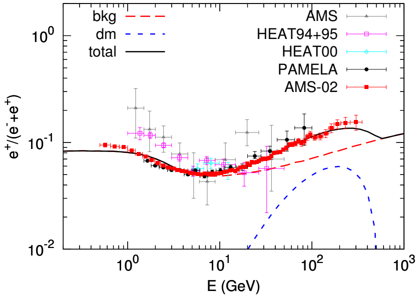


PAMELA



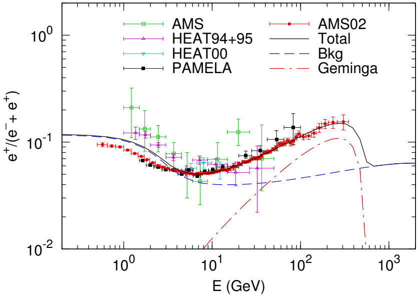


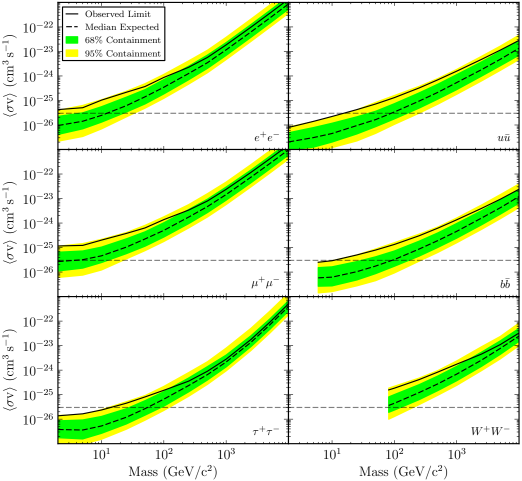
Indirect detection results



AMS-02 positron fraction interpreted by **the DM annihilation into $\tau^+\tau^-$**
[Yuan, Bi, *et al.*, arXiv:1304.1482]

AMS-02 positron fraction interpreted by **the nearby pulsar Geminga**
[Yin, ZHY, Yuan, Bi, arXiv:1304.4128]



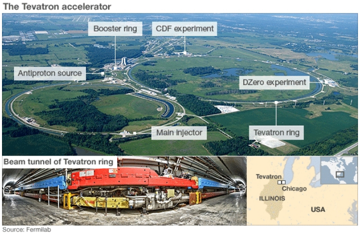


Fermi γ-ray observations on 15 dwarf spheroidal satellite galaxies of the Milky Way has set strict constraints on DM annihilations.

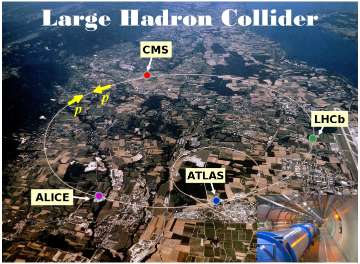
Reach down to the canonical annihilation cross section of thermal produced dark matter ($\sim 3 \times 10^{-26}$ cm^3 s^{-1}).

[arXiv:1310.0828]

Past and current hadron colliders

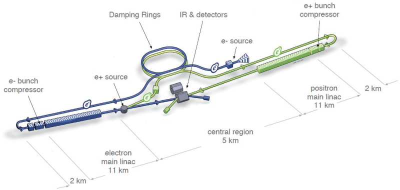


TEVATRON: $p\bar{p}$ collider
(Fermilab, 1987-2011)
Circumference: 6.28 km
Collision energy: $\sqrt{s} = 1.96$ TeV
Luminosity: $\sim 4.3 \times 10^{32}$ cm^{-2} s^{-1}
Detectors: CDF, DØ



LHC: pp collider (also pPb, PbPb)
(CERN, 2009-)
Circumference: 26.659 km
Collision energy: $\sqrt{s} = 7, 8, 13, 14$ TeV
Luminosity: $\sim 50 - 500 \times 10^{32}$ cm^{-2} s^{-1}
Detectors: ATLAS, CMS, ALICE, LHCb

Future e^+e^- colliders

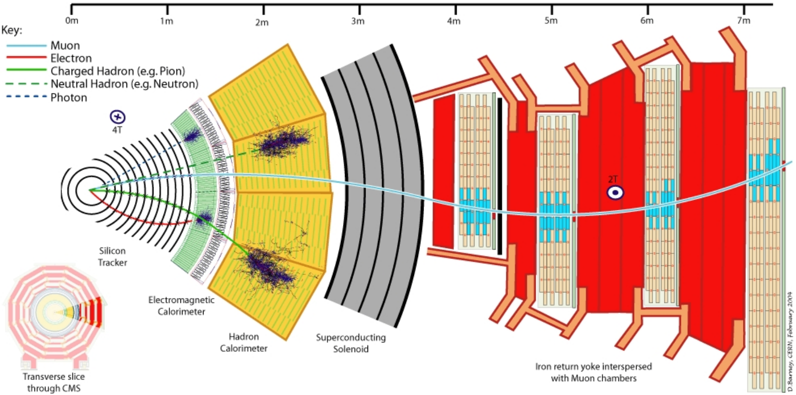


ILC: International Linear Collider
Collision energy:
$$\sqrt{s} = 250, 350, 500, 1000 \text{ GeV}$$
Luminosity: $\sim 75-500\times 10^{32}$ cm^{-2} s^{-1}
Detectors: SiD, ILD

CEPC: Circular Electron-Positron Collider (China)
Collision energy: $\sqrt{s} \sim 250$ GeV

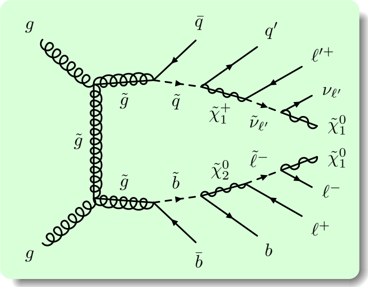
CLIC: Compact Linear Collider
Collision energy: $\sqrt{s} \sim 1-3$ TeV

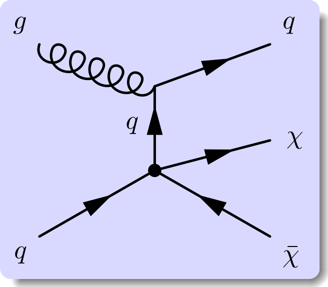
Particle identification in collider detectors



How about DM particles? **Missing energy** ($\not{E}$ or $\not{E}_{\mathrm{T}}$)
(similar to neutrinos)

DM searching channels at colliders





Social DM

Accompanied by other new particles

Complicated decay chains

Various final states

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

Maverick DM

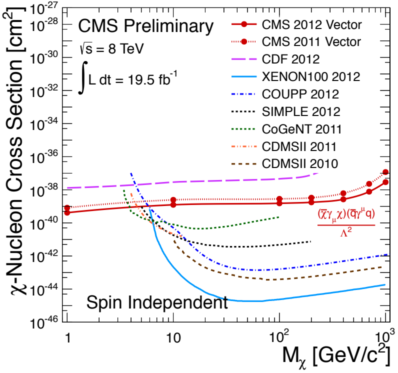
DM particle is the only new particle reachable at the collision energy

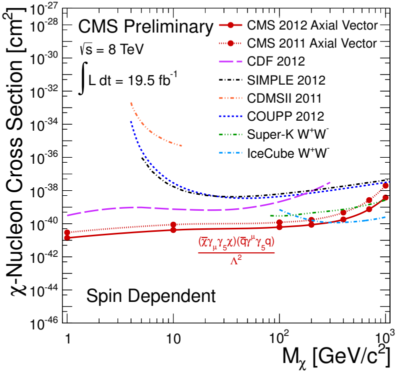
Mono-X + $\not{E}$ final states

(monojet, mono-γ, mono-W/Z, ...)

(Classified by Rocky Kolb)

Results from LHC



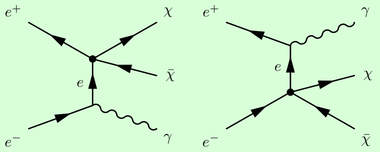


Constraints on DM-nucleon scattering cross section given by the CMS dark matter search in the monojet $+ \not{E}_T$ final state with an integrated luminosity of ~ 20 fb^{-1} at $\sqrt{s} = 8$ TeV

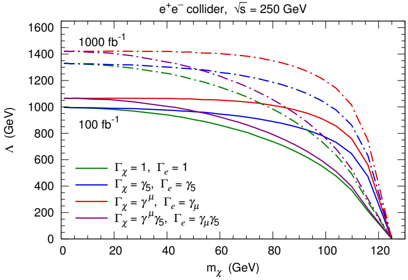
[CMS PAS EXO-12-048]

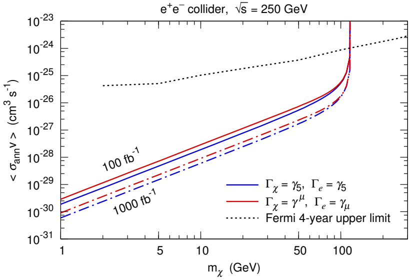
Expected sensitivity at the CEPC

Expected sensitivities (3σ reaches) to interactions between DM and electrons in the monophoton + $\not{E}$ searching channel at the circular electron-positron collider (CEPC)



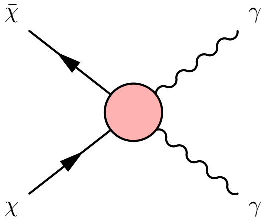
$$\mathcal{O}_e = \frac{1}{\Lambda^2}\bar{\chi}\Gamma_\chi \chi \bar{e}\Gamma_e e$$





γ-ray emission from DM: line spectrum

In general, DM particles (χ) should not have electric charge
and not directly couple to photons
$\Downarrow$
DM particles may couple to photons via high order loop diagrams
(highly suppressed, the branching fraction may be only $\sim 10^{-4} - 10^{-1}$)



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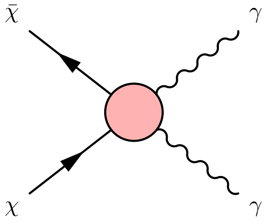


For **nonrelativistic** DM particles, the photons produced in $\chi\chi \to \gamma\gamma$ would be **mono-energetic**

$\Downarrow$

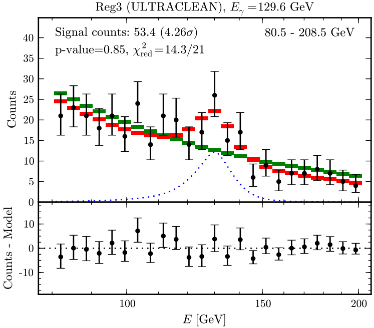
A γ-ray line at energy $\sim m_\chi$

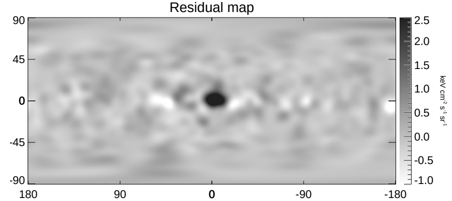
(**"smoking gun"** for DM particles)

A γ-ray line from the Galactic center region?

Using the 3.7-year Fermi-LAT γ-ray data, several analyses showed that there might be evidence of **a monochromatic γ-ray line at energy $\sim 130\,\mathrm{GeV}$**, originating from the Galactic center region (about $3-4\sigma$).

It may be due to DM annihilation with $\langle \sigma_{\rm ann} v \rangle \sim 10^{-27}\,\mathrm{cm^3\,s^{-1}}$.





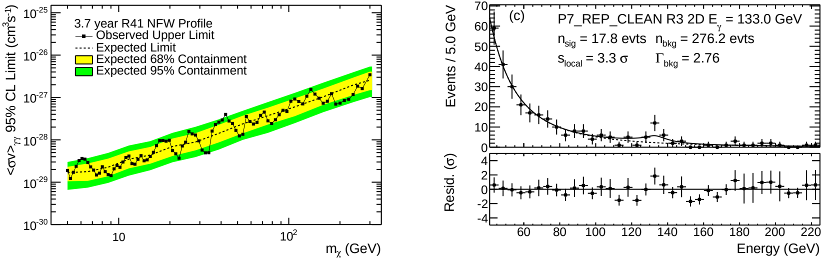
Su & Finkbeiner, 1206.1616

Weniger, 1204.2797

Recently, the Fermi-LAT Collaboration has released its official spectral line search in the energy range $5-300\,\text{GeV}$ using 3.7 years of data.

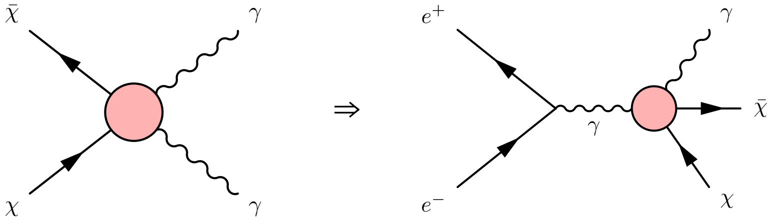
They **did not find any globally significant lines** and set 95% CL upper limits for DM annihilation cross sections.

Their most significant fit occurred at $E_\gamma = 133\,\text{GeV}$ and had **a local significance of 3.3σ**, which translates to a global significance of 1.6σ.



Fermi-LAT Collaboration, 1305.5597

DM-photon interaction at e^+e^- colliders



The coupling between DM particles and photons that induce the annihilation process $\chi\chi \to \gamma\gamma$ can also lead to the process $e^+e^- \to \chi\chi\gamma$. Therefore, the possible γ-ray line signal observed by Fermi-LAT may be tested at future TeV-scale e^+e^- colliders.

DM particles escape from the detector

$\Downarrow$

Signature: a **monophoton** associating with missing energy $(\gamma + \not{E})$

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

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

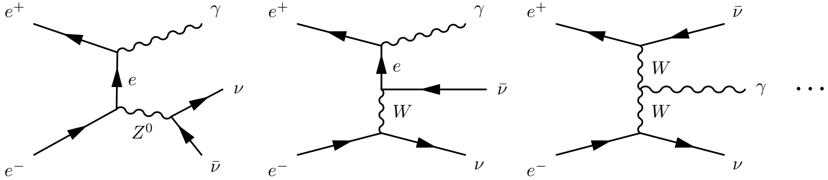
Fermi γ-ray line signal $\Longleftrightarrow$ $m_\chi \simeq 130\,\mathrm{GeV},\ \Lambda \sim 1\,\mathrm{TeV}$

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

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

Fermi γ-ray line signal $\Longleftrightarrow$ $m_\chi \simeq 130\,\mathrm{GeV},\ \Lambda \sim 3\,\mathrm{TeV}$

In the $\gamma + \not{E}$ searching channel, the main background is $e^+e^- \to \nu\bar{\nu}\gamma$:

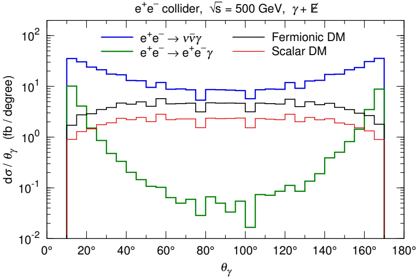


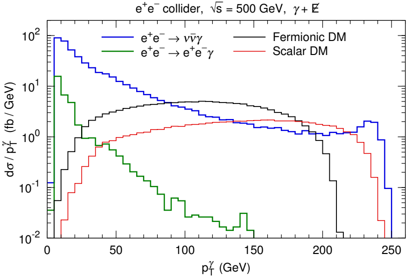
Minor backgrounds: $e^+e^- \to e^+e^-\gamma$, $e^+e^- \to \tau^+\tau^-\gamma$, $\cdots$

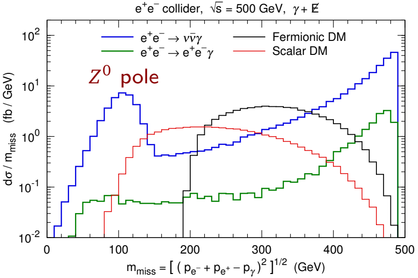
Simulation: `FeynRules` $\to$ `MadGraph 5` $\to$ `PGS 4`

ILD-like ECAL energy resolution: $\dfrac{\Delta E}{E} = \dfrac{16.6\%}{\sqrt{E/\mathrm{GeV}}} \oplus 1.1\%$

Future e^+e^- colliders: $\sqrt{s} = 250\,\mathrm{GeV}$ ("Higgs factory"), $\sqrt{s} = 500\,\mathrm{GeV}$ (typical ILC), $\sqrt{s} = 1\,\mathrm{TeV}$ (upgraded ILC & initial CLIC), $\sqrt{s} = 3\,\mathrm{TeV}$ (ultimate CLIC)





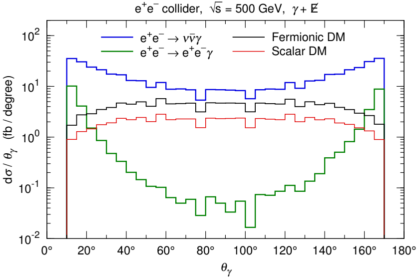


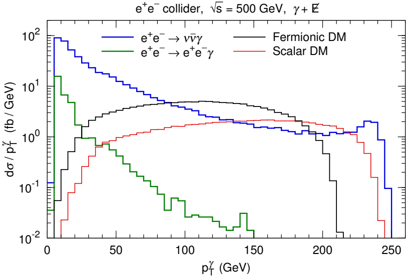
Cut 1 (pre-selection):

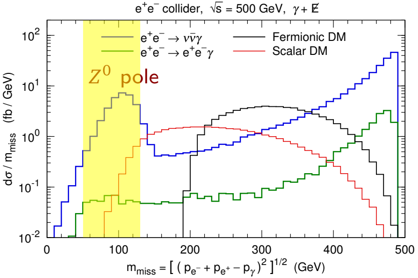
Require a photon with $E_\gamma > 10\,\text{GeV}$ and $10^\circ < \theta_\gamma < 170^\circ$

Veto any other particle

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







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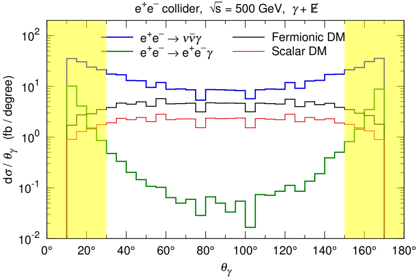

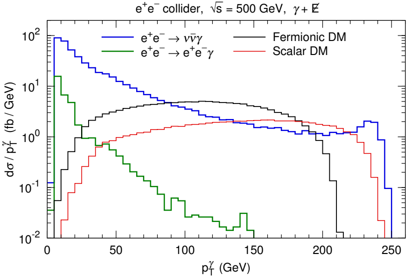

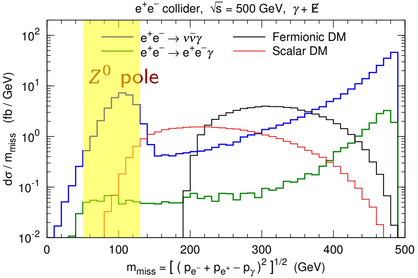

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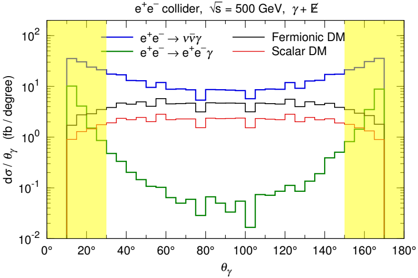

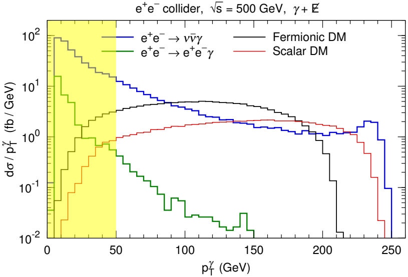

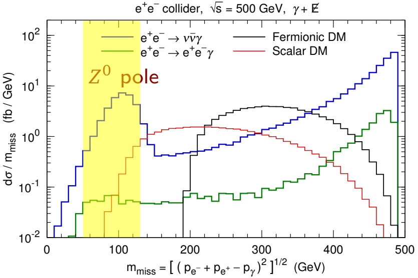

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Cut 3: Require $30^\circ < \theta_\gamma < 150^\circ$

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

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

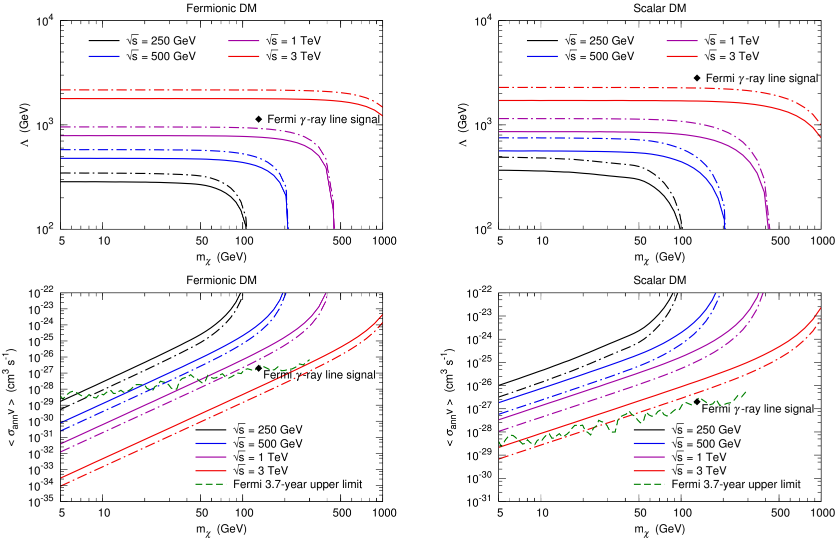
Most of the signal events remain

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

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

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

Collider sensitivity



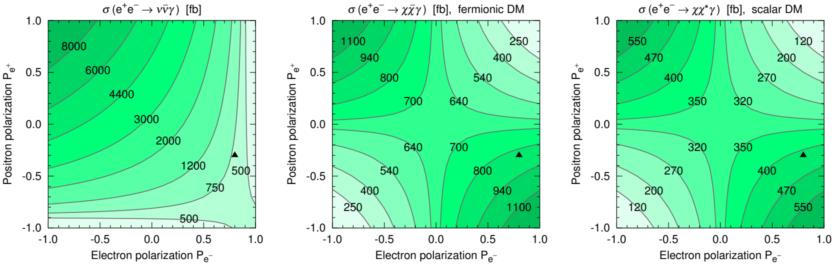
Solid lines: $100\,\mathrm{fb}^{-1}$; dot-dashed lines: $1000\,\mathrm{fb}^{-1}$ $(S/\sqrt{B} = 3)$

[ZHY, Yin, Yan, arXiv:1307.5740]

Beam polarization

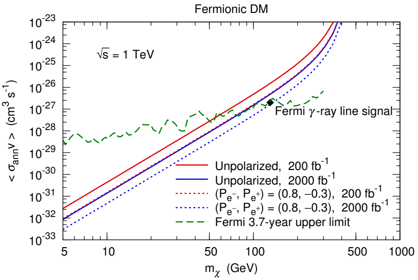
For a process at an e^+e^- collider with **polarized beams**,

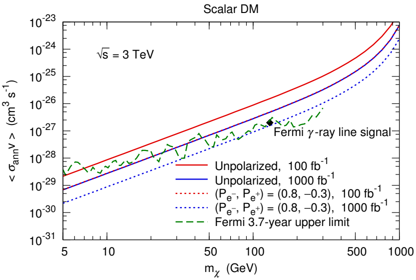
$$\sigma(P_{e^-}, P_{e^+}) = \frac{1}{4}\left[(1+P_{e^-})(1+P_{e^+})\sigma_{\mathrm{RR}} + (1-P_{e^-})(1-P_{e^+})\sigma_{\mathrm{LL}} + (1+P_{e^-})(1-P_{e^+})\sigma_{\mathrm{RL}} + (1-P_{e^-})(1+P_{e^+})\sigma_{\mathrm{LR}}\right]$$



▲ $(P_{e^-}, P_{e^+}) = (0.8, -0.3)$ **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 Fermi γ-ray line signal at an e^+e^- collider with $\sqrt{s} = 1\,\mathrm{TeV}$ $(3\,\mathrm{TeV})$.

[ZHY, Yin, Yan, arXiv:1307.5740]

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

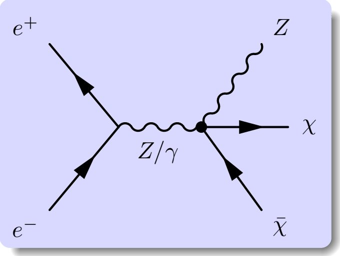
The mono-Z channel at high energy e^+e^- collider can be sensitive to **the DM coupling to $ZZ/Z\gamma$.**

We consider the following couplings:

$$\mathcal{O}_{\rm F1} = \frac{1}{\Lambda_1^3}\bar{\chi}\chi B_{\mu\nu}B^{\mu\nu} + \frac{1}{\Lambda_2^3}\bar{\chi}\chi W^a_{\mu\nu}W^{a\mu\nu}$$
$$\supset \bar{\chi}\chi(G_{\rm ZZ}Z_{\mu\nu}Z^{\mu\nu} + G_{\rm AZ}A_{\mu\nu}Z^{\mu\nu})$$

$$\mathcal{O}_{\rm F2} = \frac{1}{\Lambda_1^3}\bar{\chi}i\gamma_5\chi B_{\mu\nu}\tilde{B}^{\mu\nu} + \frac{1}{\Lambda_2^3}\bar{\chi}i\gamma_5\chi W^a_{\mu\nu}\tilde{W}^{a\mu\nu}$$
$$\supset \bar{\chi}i\gamma_5\chi(G_{\rm ZZ}Z_{\mu\nu}\tilde{Z}^{\mu\nu} + G_{\rm AZ}A_{\mu\nu}\tilde{Z}^{\mu\nu})$$

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

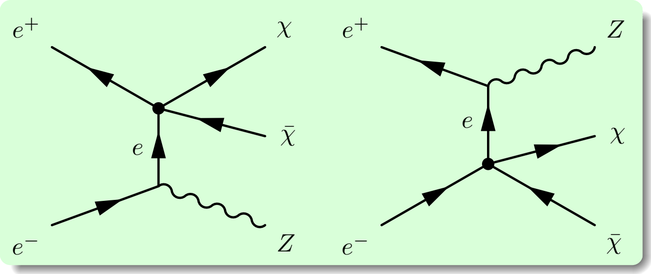


$$G_{\rm ZZ} \equiv \frac{\sin^2\theta_W}{\Lambda_1^3} + \frac{\cos^2\theta_W}{\Lambda_2^3}$$

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

Mono-Z signature: DM couplings to electrons

This channel can also be sensitive to **the DM coupling to electrons.**



We consider the following couplings:

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

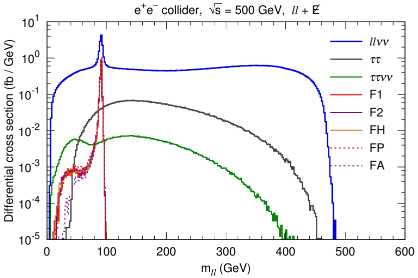
Lepton channel: $Z \to \ell^+\ell^-$ $(\ell = e, \mu)$

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

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

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

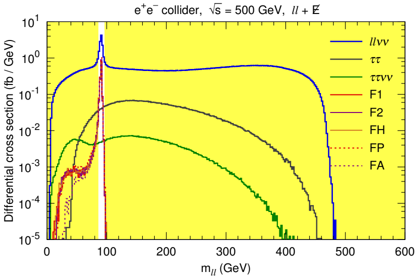
Reconstructing the Z boson: require only 2 leptons (e's or μ's) with $p_{\mathrm{T}} > 10$ GeV and $|\eta| < 3$, and that they are opposite-sign same-flavor;



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

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

Reconstructing the Z boson: require only 2 leptons (e's or μ's) with $p_T > 10$ GeV and $|\eta| < 3$, and that they are opposite-sign same-flavor; require their invariant mass satisfying $|m_{\ell\ell} - m_Z| < 5$ GeV.

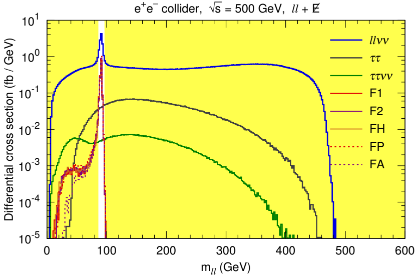


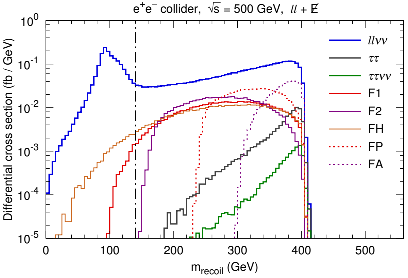
Lepton channel: $Z \to \ell^+\ell^-$ $(\ell = e, \mu)$

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

Reconstructing the Z boson: require only 2 leptons (e's or μ's) with $p_\mathrm{T} > 10$ GeV and $|\eta| < 3$, and that they are opposite-sign same-flavor; require their invariant mass satisfying $|m_{\ell\ell} - m_Z| < 5$ GeV.

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



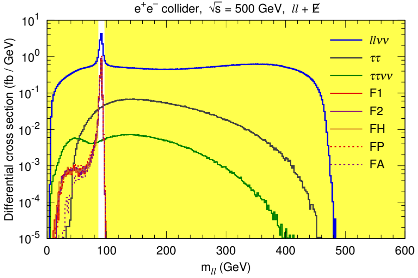


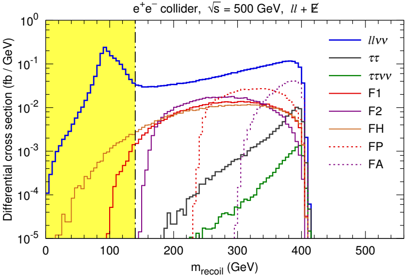
Lepton channel: $Z \to \ell^+\ell^-$ $(\ell = e, \mu)$

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

Reconstructing the Z boson: require only 2 leptons (e's or μ's) with $p_T > 10$ GeV and $|\eta| < 3$, and that they are opposite-sign same-flavor; require their invariant mass satisfying $|m_{\ell\ell} - m_Z| < 5$ GeV.

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





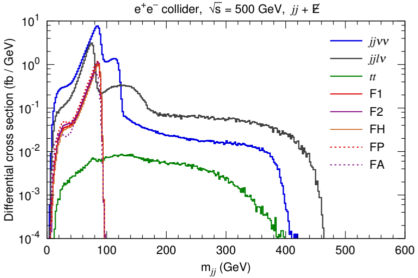
Hadron channel: $Z \to jj$

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

Hadron channel: $Z \to jj$

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

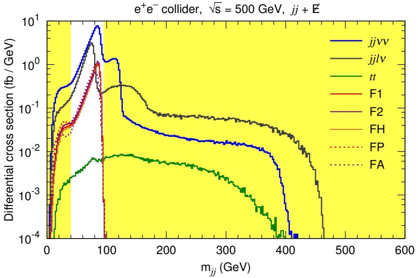
Reconstructing the Z boson: require only 2 jets with $p_{\mathrm{T}} > 10$ GeV and $|\eta| < 3$;



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 $p_T > 10$ GeV and $|\eta| < 3$; require their invariant mass satisfying 40 GeV $< m_{jj} <$ 95 GeV.

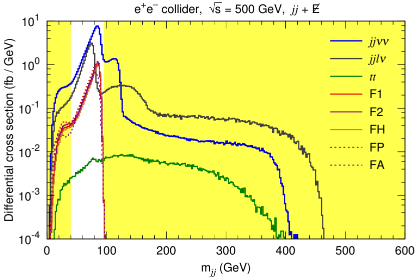


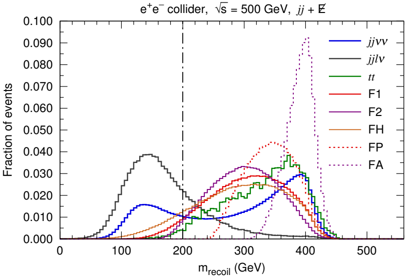
Hadron channel: $Z \to jj$

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

Reconstructing the Z boson: require only 2 jets with $p_T > 10$ GeV and $|\eta| < 3$; require their invariant mass satisfying 40 GeV $< m_{jj} <$ 95 GeV.

Reconstructing the recoil mass: $m_{\text{recoil}} = \sqrt{(p_{e^+} + p_{e^-} - p_{j_1} - p_{j_2})^2}$;





Hadron channel: $Z \to jj$

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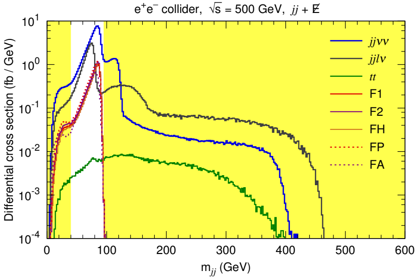
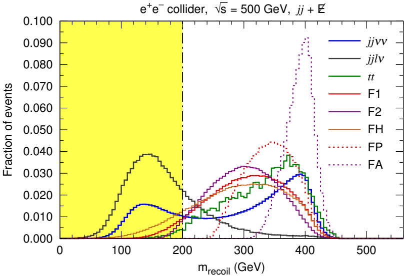
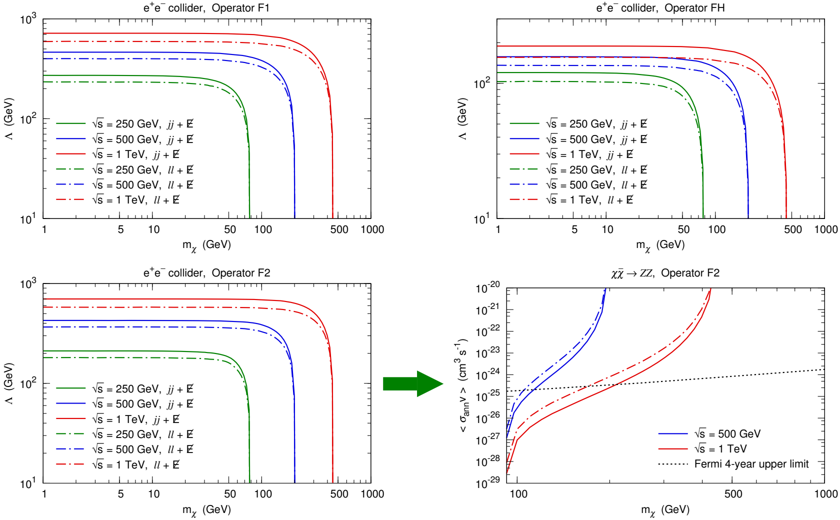
Reconstructing the Z boson: require only 2 jets with $p_T > 10$ GeV and $|\eta| < 3$; require their invariant mass satisfying 40 GeV $< m_{jj} <$ 95 GeV.

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



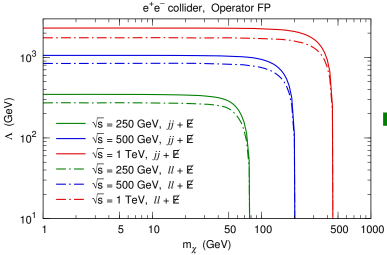


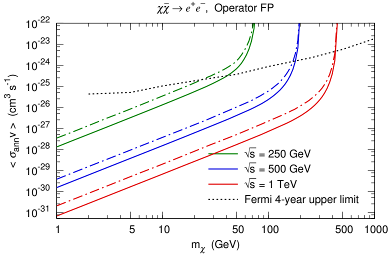
3σ sensitivity: DM couplings to $ZZ/Z\gamma$

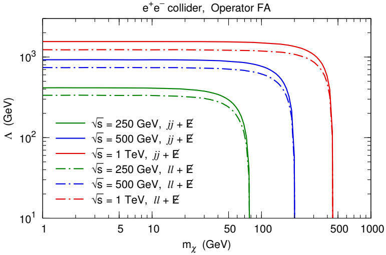


(with an integrated luminosity of 1000 fb^{-1}, assuming $\Lambda = \Lambda_1 = \Lambda_2$ for $\mathcal{O}_{F1}$ and $\mathcal{O}_{F2}$)

3σ sensitivity: DM couplings to electrons







(with an integrated luminosity of 1000 fb^{-1})

Conclusions and discussions

1. As a frontier of cosmology, astrophysics, and particle physics, the research of **dark matter** connects our knowledge of the Universe from the largest to the smallest scales.
2. In addition to DM direct and indirect detection, **collider detection** provides an independent and complementary way to explore the **microscopic nature** of DM particles.
3. If there are other new particles accompanied with DM particles, collider detection is needed to acquire **the most detailed information** about the new physics containing DM particles.

Thanks for your attentions!