Searching for dark matter via coupling to photons at e^+e^- colliders

Zhao-Huan YU (余钊焕)

Institute of High Energy Physics, CAS

with Xiao-Jun BI, Qi-Shu YAN and Peng-Fei YIN

Work in progress

June 29, 2013

DM-photon interaction

In general, dark matter (DM) are not luminous

$\Downarrow$

DM particles (χ) should not have electric charge and not directly couple to photons

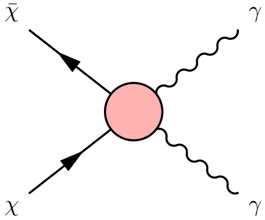
DM-photon interaction

In general, dark matter (DM) are not luminous

$\Downarrow$

DM particles (χ) should not have electric charge and not directly couple to photons

However, DM particles may couple to photons via loop diagrams



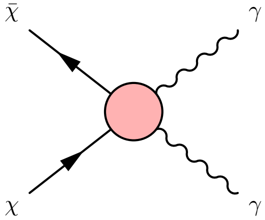
DM-photon interaction

In general, dark matter (DM) are not luminous

$\Downarrow$

DM particles (χ) should not have electric charge
and not directly couple to photons

However, DM particles may couple to photons via loop diagrams



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

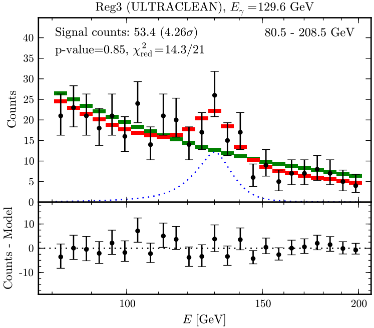
$\Downarrow$

A γ-ray line at energy $\sim m_\chi$
(**"smoking gun"** for DM particles)

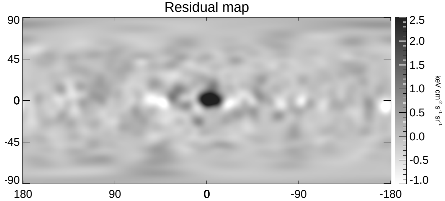
A γ-ray line from the Galactic center region?

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 ~ 130 GeV**, originating from the Galactic center region (about $3-4\sigma$).

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



Weniger, 1204.2797

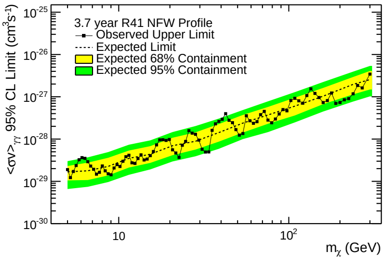


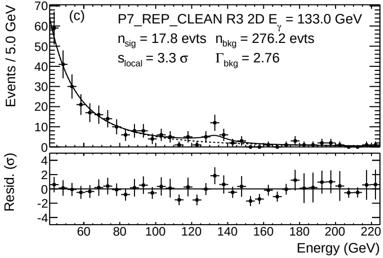
Su & Finkbeiner, 1206.1616

Recently, the Fermi-LAT Collaboration has released its official spectral line search in the energy range $5 - 300$ 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.

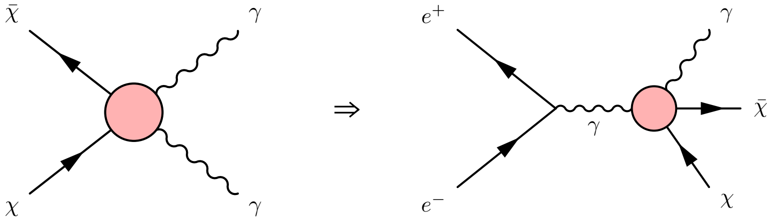
Their most significant fit occurred at $E_\gamma = 133$ GeV and had **a local significance of 3.3σ**, which translates to a global significance of 1.6σ.





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

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

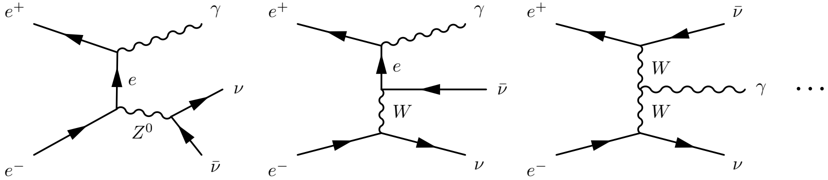
Fermi γ-ray line signal $\Longleftrightarrow$ $m_\chi \simeq 130$ GeV, $\Lambda \sim 1$ TeV

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

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

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

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

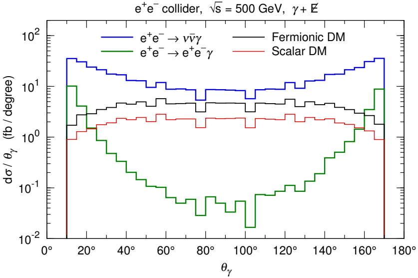


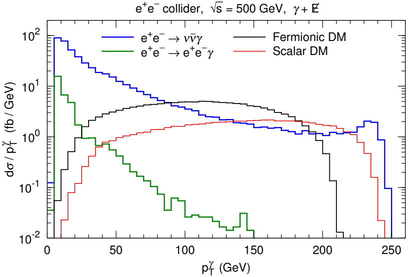
Minor backgrounds: $e^+e^- \to e^+e^-\gamma$, $e^+e^- \to \tau^+\tau^-\gamma$, $\cdots$

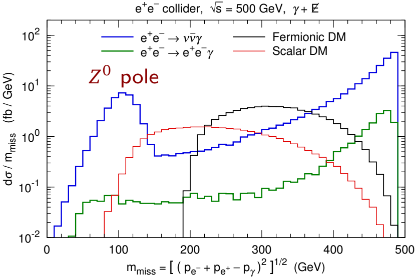
Simulation: `FeynRules` → `MadGraph 5` → `PGS 4`

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

Consider $\sqrt{s} = 250$ GeV ("Higgs factory"), $\sqrt{s} = 500$ GeV (typical ILC), $\sqrt{s} = 1$ TeV (initial CLIC), and $\sqrt{s} = 3$ TeV (ultimate CLIC)



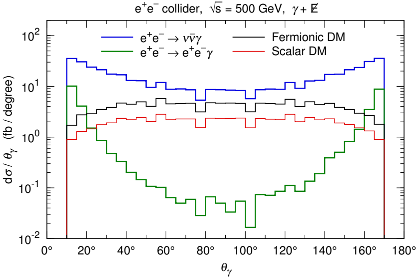


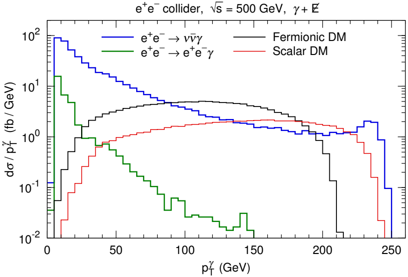


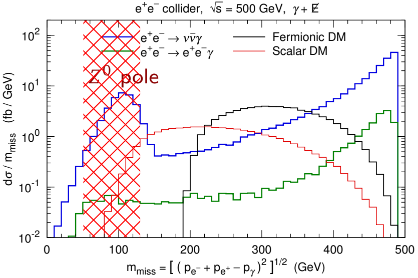
Step 1 (pre-selection):

Require a photon with $E_\gamma > 10$ GeV
and $10^\circ < \theta_\gamma < 170^\circ$
Veto any other particle

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



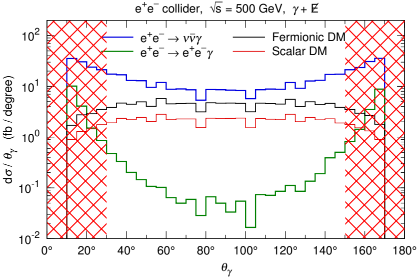


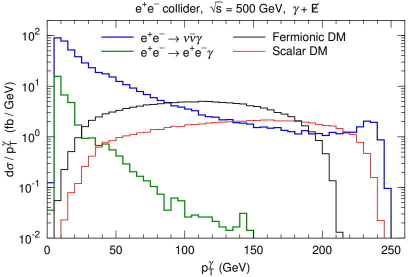


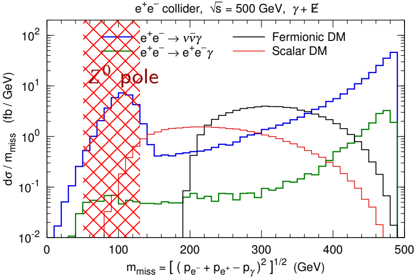
Step 1 (pre-selection):
Require a photon with $E_\gamma > 10$ GeV
and $10^\circ < \theta_\gamma < 170^\circ$
Veto any other particle

Step 2: Veto 50 GeV $< m_{\text{miss}} <$ 130 GeV

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





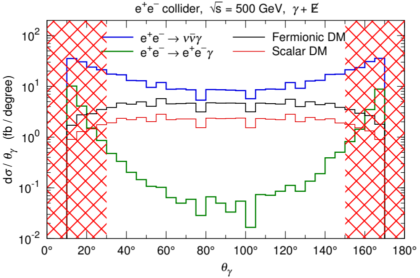


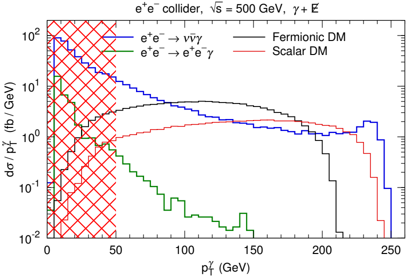
Step 1 (pre-selection):
Require a photon with $E_\gamma > 10$ GeV and $10^\circ < \theta_\gamma < 170^\circ$
Veto any other particle

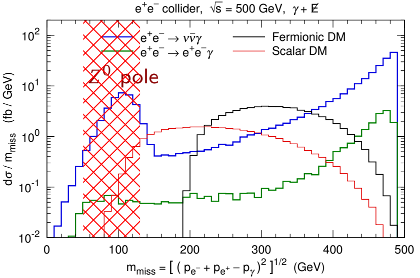
Step 2: Veto 50 GeV $< m_{\rm miss} <$ 130 GeV

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

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







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

Step 2: Veto 50 GeV $< m_{\text{miss}} <$ 130 GeV

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

Step 4: Require $p_T^\gamma > \sqrt{s}/10$

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

Production cross sections after each step of event selection

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

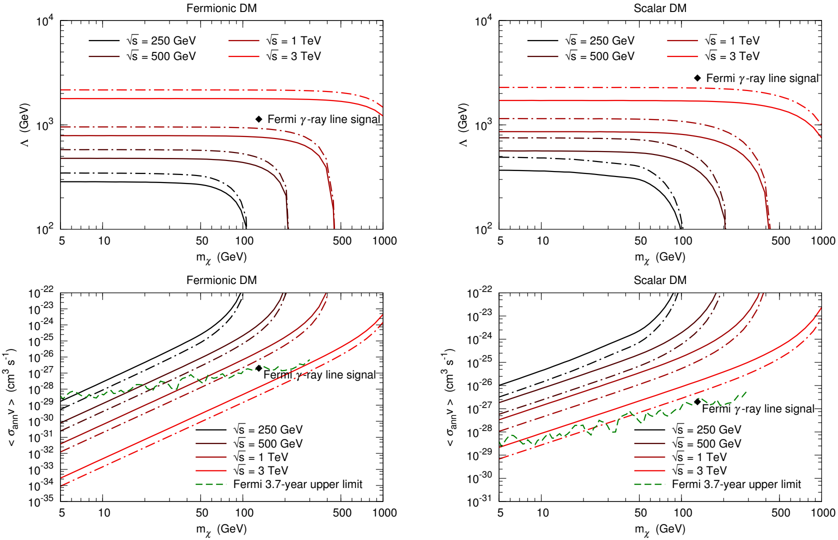
Benchmark point: $\Lambda = 200$ GeV, $m_\chi = 100\,(50)$ GeV for fermionic (scalar) DM

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

$(\sqrt{s} = 500$ GeV$)$



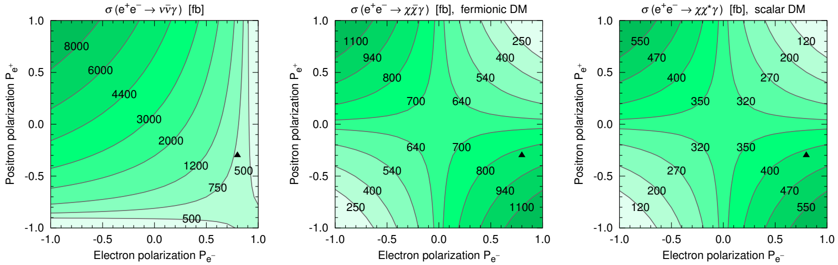
Solid lines: 100 fb^{-1}; dot-dashed lines: 1000 fb^{-1} $(S/\sqrt{B} = 3)$

ILC luminosity: $\sim 500\ \text{fb}^{-1}/\text{year}$ [ILC technical design report, Vol. 1, 1306.6327]

Beam polarization

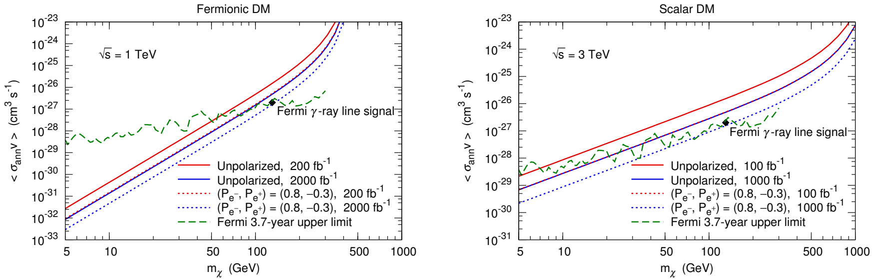
For a process at an e^+e^- collider with **polarized beams**,

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



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

S-matrix unitarity

For quantum scattering theories,

S-matrix unitarity ($S^\dagger S = 1$) $\Longleftrightarrow$ conservation of probability

In order to preserve probability, at any order of a perturbative theory, the S-matrix unitarity should not be violated.

When a process described by an effective theory violate the unitarity, it means that the theory is invalid for this process and a UV-complete theory is needed for a full description.

The effective operator treatment for DM searches at colliders should be carefully checked by verifying the S-matrix unitarity.

Unitarity conditions

The $2 \to 2$ amplitude $\mathcal{M}(\cos\theta)$ can be expanded as partial waves:

$$\mathcal{M}(\cos\theta) = 16\pi \sum_j (2j+1) a_j P_j(\cos\theta), \quad a_j = \frac{1}{32\pi} \int_{-1}^{1} d\cos\theta P_j(\cos\theta) \mathcal{M}(\cos\theta)$$

Unitarity condition for $2 \to 2$ **elastic scattering**: $\left|\mathrm{Re}\, a_j^{\mathrm{el}}\right| \le \frac{1}{2}, \quad \forall j$

Unitarity condition for $2 \to 2$ **inelastic scattering**: $\left|a_j^{\mathrm{inel}}\right| \le \frac{1}{2\sqrt{\beta_f}}, \quad \forall j$

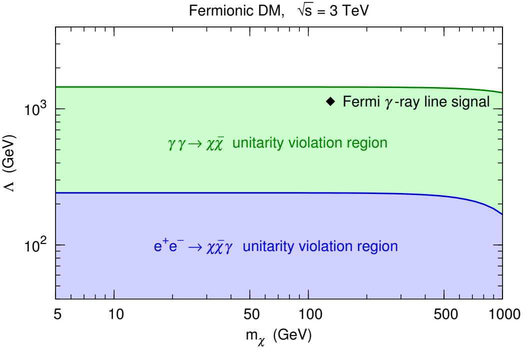
(β_f is the velocity of either of the final particles)

For $2 \to n$ **inelastic scattering**, we introduce a quantity

$$b_j^{\mathrm{inel}} \equiv \frac{1}{64\pi} \int d\cos\theta_{\alpha\beta} P_j(\cos\theta_{\alpha\beta}) \int d\Pi_{\gamma_n} \mathcal{M}^*_{\beta\to\gamma_n} \mathcal{M}_{\alpha\to\gamma_n} (2\pi)^4 \delta^{(4)}(p_\alpha - p_{\gamma_n}),$$

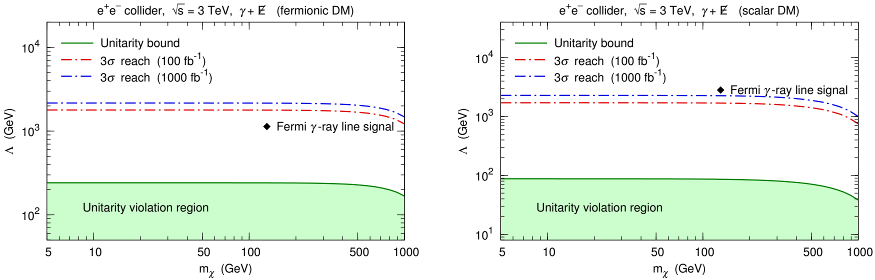
and it can be proved that the unitarity condition would be $b_j^{\mathrm{inel}} \le \frac{1}{4}, \quad \forall j$.

Unitarity bounds: $2 \to 2$ vs $2 \to 3$



Given the same $\sqrt{s}$, unitarity bounds for $2 \to 2$ scattering are **much more stringent** than those for $2 \to 3$ scattering.

However, here the relevant bounds are those for $2 \to 3$ scattering.



All the experimental reaches we obtained lie far beyond the unitarity violation regions.

From the viewpoint of S-matrix unitarity, our effective operator treatment do not exceed its valid range.

Conclusions and discussions

1. We explore the prospect of the DM searching via **the coupling between DM and photons** at TeV-scale e^+e^- colliders through an effective operator approach.
2. **The fermionic DM searching** at e^+e^- colliders would be **more sensitive** than Fermi-LAT for **light DM particles**. With a data set of 100 fb^{-1}, the possible Fermi γ-ray line signal for fermionic DM can be **easily tested** at a 3 TeV collider.
3. **The scalar DM searching** would be **much more difficult**, and even an integrated luminosity of 1000 fb^{-1} would be **not enough** to test the Fermi signal at $\sqrt{s} = 3$ TeV.

Conclusions and discussions

4. Using the **polarized beams** is roughly equivalent to **collecting 10 times of data**.
5. After considering a realistic polarization configuration, the Fermi signal for fermionic DM **can be tested** with 2000 fb^{-1} data at $\sqrt{s} = 1$ TeV, while a data set of 1000 fb^{-1} would be **just sufficient to test** the Fermi signal for scalar DM at a 3 TeV collider.
6. In order to check the validity of the effective operator approach, we derive **a general unitarity condition for $2 \to n$ processes**. Our effective operator treatment **does not exceed its valid range** from the viewpoint of unitarity.

Thanks for your attentions!

Backup slides

Note that our unitarity condition $b_j^{\text{inel}} \leq \frac{1}{4}$ is derived without any approximation.

Through an approximate method, a unitarity bound on the $2 \to n$ inelastic cross section $\sigma_{\text{inel}}(2 \to n)$ can be derived to be

$$\sigma_{\text{inel}}(2 \to n) \leq \frac{4\pi}{s}.$$

[Dicus & H. -J. He, hep-ph/0409131]

We have compared the results given by these two formulas and find that **their differences are rather small** for the processes considered here.