Potential dark matter γ-ray line signature observed by Fermi-LAT and its test at high energy e^+e^- colliders

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γ-ray emission from DM: continuous spectrum

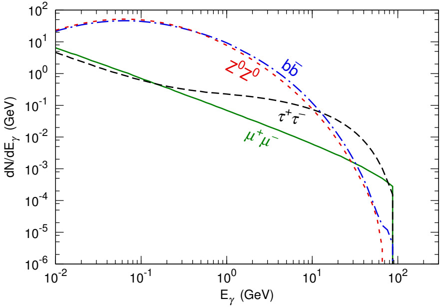
Dark matter (DM, χ) pair annihilation or decay into

e^+e^-, $\mu^+\mu^-$, $\tau^+\tau^-$, $q\bar{q}$, W^+W^-, Z^0Z^0, h^0h^0

$\Downarrow$

Gamma-ray emission from final state radiation or decay

Cut-off energy: m_χ for DM annihilation, $m_\chi/2$ for DM decay



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Gamma-ray emission from final state radiation or decay

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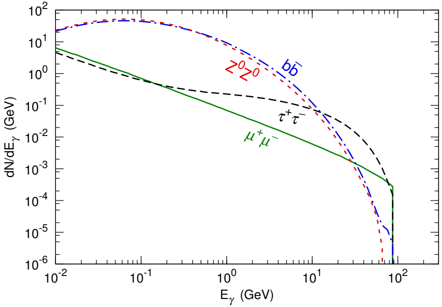
Searching for DM signature in DM-dominant regions:

Galactic center
Galactic halo
dwarf spheroidal galaxies
clusters of galaxies



γ-ray emission from DM: line spectrum

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

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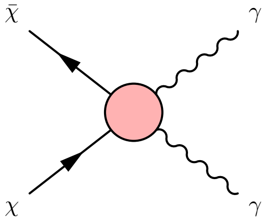
DM particles may couple to photons via high order loop diagrams

(highly suppressed, the branching fraction may be only $\sim 10^{-4} - 10^{-1}$)



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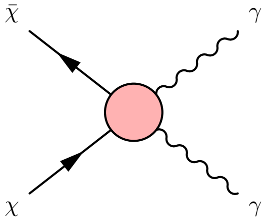


For **nonrelativistic** DM particles, the photons produced in $\chi\chi \to \gamma\gamma$ would be **mono-energetic**

$\Downarrow$

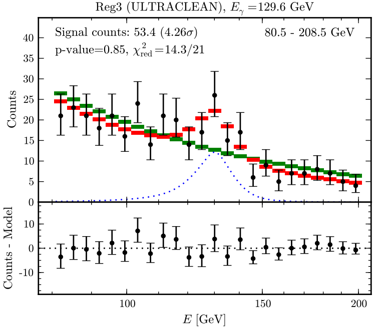
A γ-ray line at energy $\sim m_\chi$

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

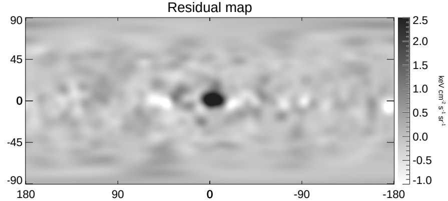
A γ-ray line from the Galactic center region?

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

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



Weniger, 1204.2797

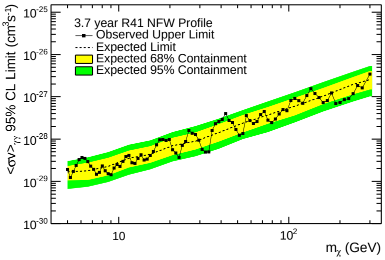


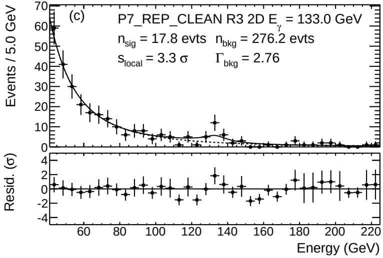
Su & Finkbeiner, 1206.1616

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.

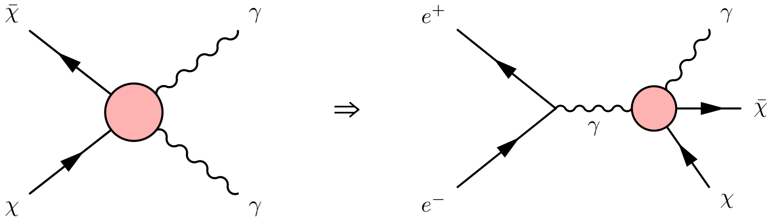
Their most significant fit occurred at $E_\gamma = 133$ GeV and had **a local significance of** 3.3σ, which translates to a global significance of 1.6σ.





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

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

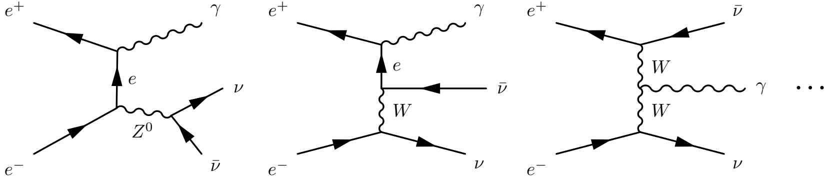
Fermi γ-ray line signal $\iff$ $m_\chi \simeq 130$ GeV, $\Lambda \sim 1$ TeV

For complex scalar DM, 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 $\iff$ $m_\chi \simeq 130$ GeV, $\Lambda \sim 3$ TeV

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

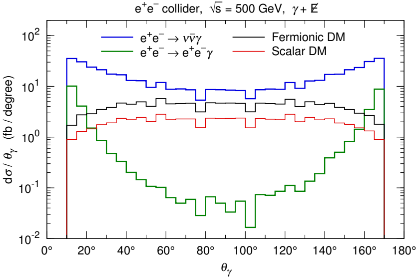


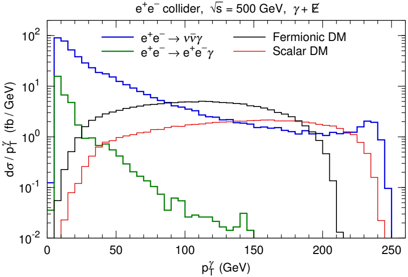
Minor backgrounds: $e^+e^- \to e^+e^-\gamma$, $e^+e^- \to \tau^+\tau^-\gamma$, $\cdots$

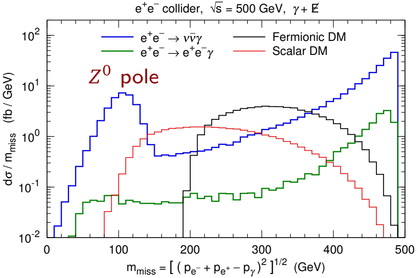
Simulation: `FeynRules` $\to$ `MadGraph 5` $\to$ `PGS 4`

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

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





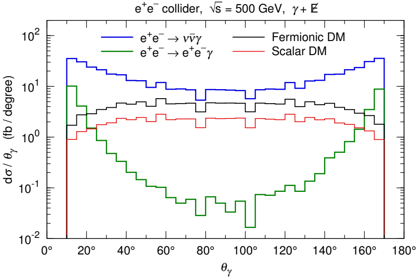


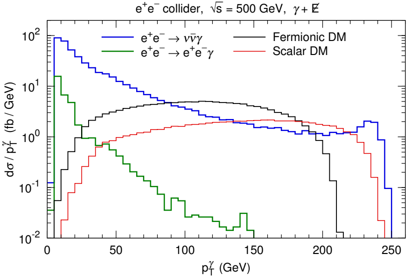
Cut 1 (pre-selection):

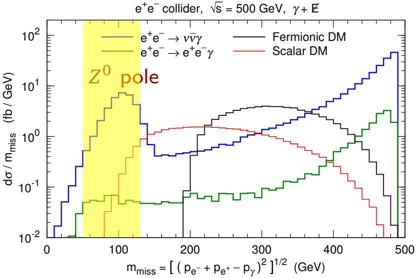
Require a photon with $E_\gamma > 10$ GeV and $10^\circ < \theta_\gamma < 170^\circ$

Veto any other particle

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







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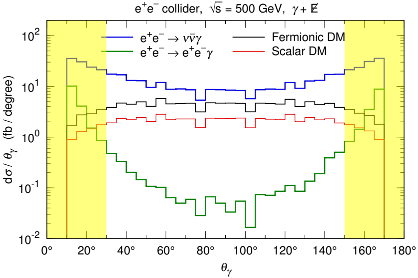

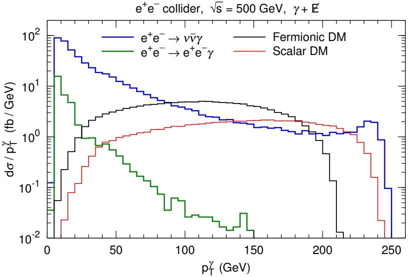

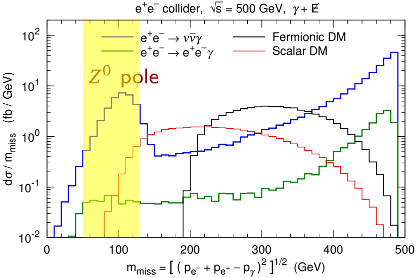

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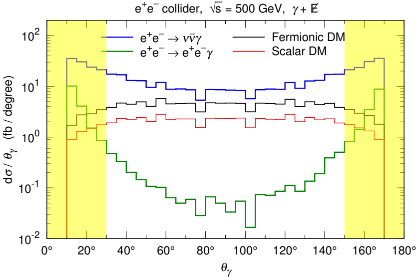

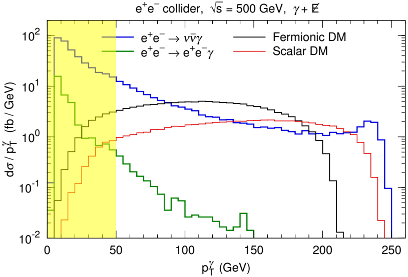

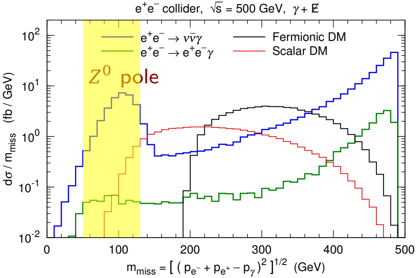

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Cut 4: Require $p_T^\gamma > \sqrt{s}/10$

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

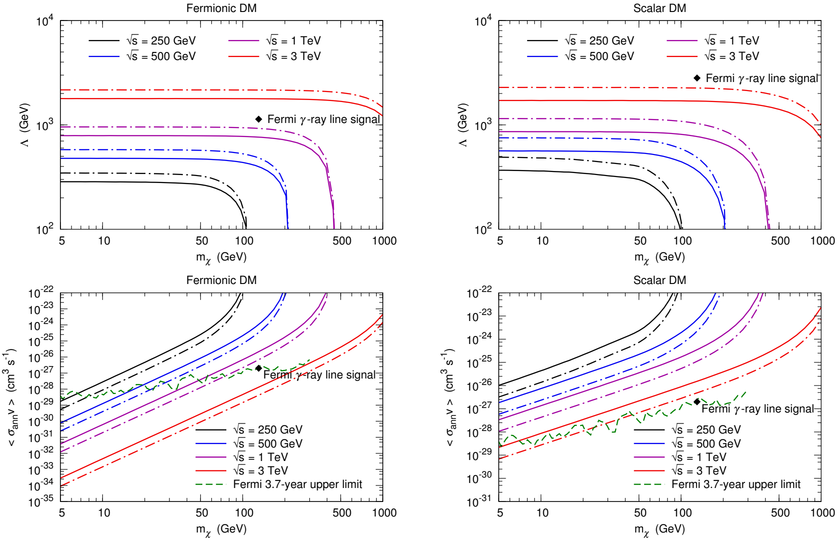
Benchmark point: $\Lambda = 200$ GeV, $m_\chi = 100\,(50)$ GeV for fermionic (scalar) DM

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

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



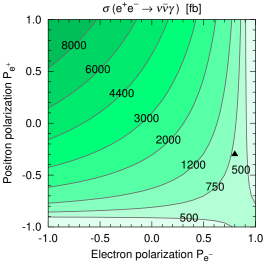
Solid lines: 100 fb^{-1}; dot-dashed lines: 1000 fb^{-1} $(S/\sqrt{B} = 3)$

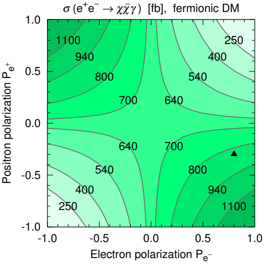
ILC luminosity: $240 - 570\ \text{fb}^{-1}/\text{year}$ [ILC TDR, Vol. 1, 1306.6327]

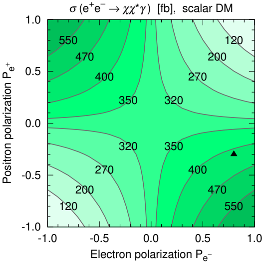
Beam polarization

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

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

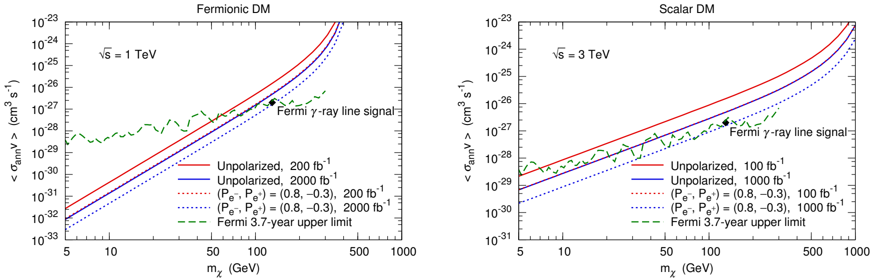






▲ $(P_{e^-}, P_{e^+}) = (0.8, -0.3)$ **can be achieved at the ILC**

[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 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**

A process violate the unitarity in a non-renormalizable effective theory

$\Downarrow$

The theory is **invalid** for this process

$\Downarrow$

A **UV-complete theory** may be 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)

$$S^\dagger S = 1,\ S = 1 + iT \quad \Rightarrow \quad -i(T - T^\dagger) = T^\dagger T$$

$$\Downarrow$$

$$-i(\mathcal{M}_{\alpha\to\beta} - \mathcal{M}^*_{\beta\to\alpha}) = \sum_\gamma \int d\Pi_\gamma \mathcal{M}^*_{\beta\to\gamma}\mathcal{M}_{\alpha\to\gamma}(2\pi)^4\delta^{(4)}(p_\alpha - p_\gamma)$$

$$\Downarrow$$

$$\begin{aligned} 2\,\mathrm{Im}\,\mathcal{M}_{\mathrm{el}}(\cos\theta_{\alpha\beta}) &= \int d\Pi_{\gamma_{\mathrm{el}}}\mathcal{M}^*_{\beta\to\gamma_{\mathrm{el}}}\mathcal{M}_{\alpha\to\gamma_{\mathrm{el}}}(2\pi)^4\delta^{(4)}(p_\alpha - p_{\gamma_{\mathrm{el}}}) \\ &\quad + \int d\Pi_{\gamma_n}\mathcal{M}^*_{\beta\to\gamma_n}\mathcal{M}_{\alpha\to\gamma_n}(2\pi)^4\delta^{(4)}(p_\alpha - p_{\gamma_n}) + \text{ other inelastic terms} \\ &\geq \frac{1}{32\pi^2}\int d\Omega_{k_1}\mathcal{M}^*_{\mathrm{el}}(\cos\theta_{\beta\gamma})\mathcal{M}_{\mathrm{el}}(\cos\theta_{\alpha\gamma}) + \int d\Pi_{\gamma_n}\mathcal{M}^*_{\beta\to\gamma_n}\mathcal{M}_{\alpha\to\gamma_n}(2\pi)^4\delta^{(4)}(p_\alpha - p_{\gamma_n}) \end{aligned}$$

$$\Downarrow$$

$$\mathrm{Im}\,a_j^{\mathrm{el}} \geq |a_j^{\mathrm{el}}|^2 + |b_j^{\mathrm{inel}}|^2,$$

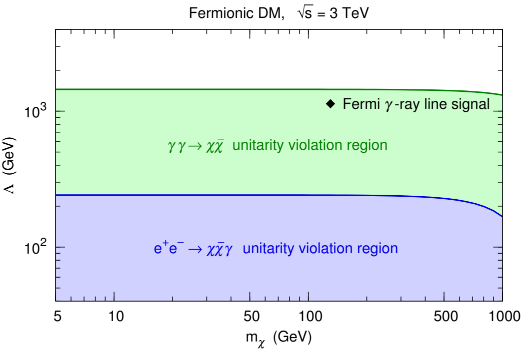
$$|b_j^{\mathrm{inel}}|^2 \equiv \frac{1}{64\pi}\int d\cos\theta_{\alpha\beta}P_j(\cos\theta_{\alpha\beta})\int d\Pi_{\gamma_n}\mathcal{M}^*_{\beta\to\gamma_n}\mathcal{M}_{\alpha\to\gamma_n}(2\pi)^4\delta^{(4)}(p_\alpha - p_{\gamma_n})$$

$$\Downarrow$$

Unitarity condition for any $2 \to n$ **inelastic scattering**:

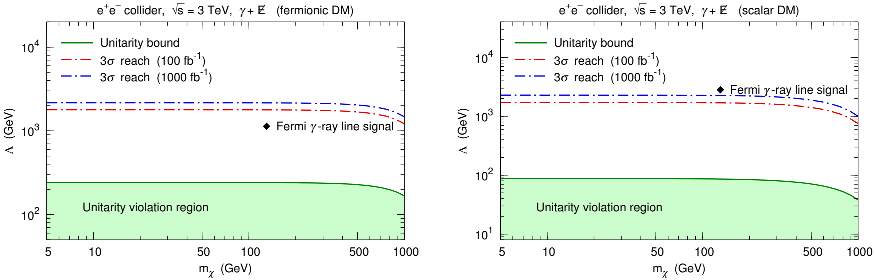
$$\left|b_j^{\mathrm{inel}}\right| \leq \frac{1}{2}, \quad \forall j$$

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

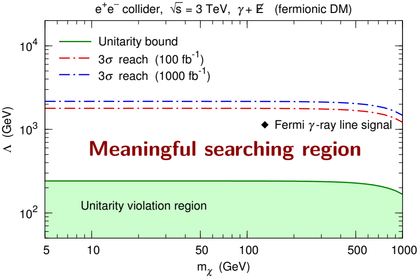


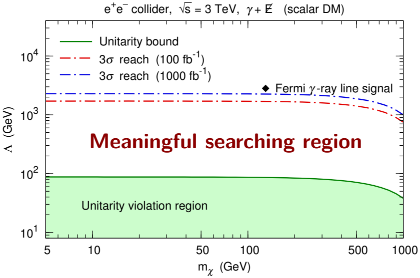
Given the same $\sqrt{s}$, unitarity bounds for $2 \to 2$ scattering are **much more stringent** than those for $2 \to 3$ scattering.

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.





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

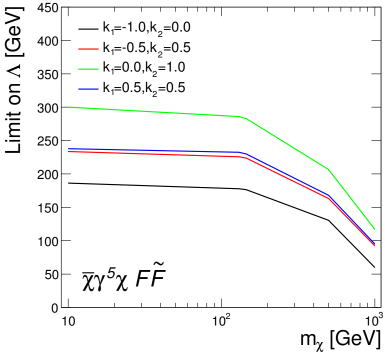
1. There is a potential **γ-ray line signature** in the Fermi-LAT data. It can be interpreted as the result of the DM annihilation into photons.
2. With a 100 fb^{-1} dataset, the potential γ-ray line signature for **the fermionic DM can be tested** at a 3 TeV e^+e^- collider, though **the scalar DM searching would be challenging**.
3. Using the **polarized beams** is roughly equivalent to **collecting 10 times of data**.
4. In order to check the validity of the effective operator approach, we derive **a general unitarity condition for $2 \to n$ processes**. **The experimental reaches we obtained are valid** since they lie far beyond the unitarity violation regions.

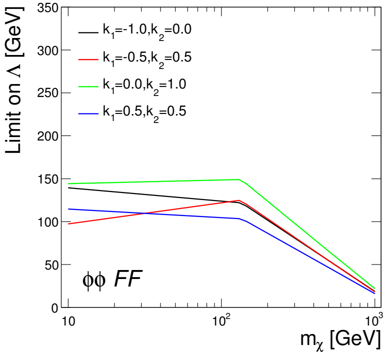
Thanks for your attentions!

Backup slides

Recent LHC sensitivity

Reinterpreting an ATLAS $\gamma + \not{E}_T$ analysis with an integrated luminosity of 4.6 fb^{-1} at $\sqrt{s} = 7$ TeV, Nelson *et al.* [1307.5064] derived constraints on the DM-photon interaction, only up to $\Lambda \sim 100 - 300$ GeV.





An approximate unitarity condition

Note that our unitarity condition $\left|b_j^{\rm inel}\right| \le \frac{1}{2}$ is derived without any approximation.

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

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

[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.

Unitarity condition in terms of amplitudes:

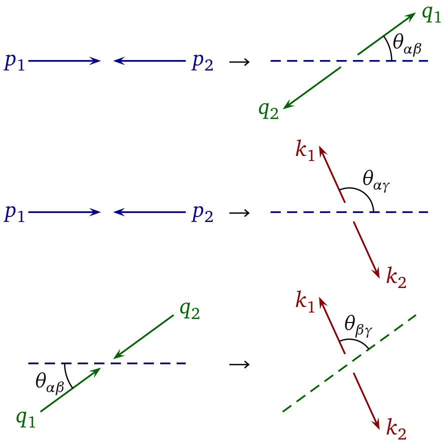
$$-i(\mathcal{M}_{\alpha\to\beta} - \mathcal{M}^*_{\beta\to\alpha}) = \sum_{\gamma} \int d\Pi_\gamma \mathcal{M}^*_{\beta\to\gamma}\mathcal{M}_{\alpha\to\gamma}(2\pi)^4\delta^{(4)}(p_\alpha - p_\gamma)$$

For **the elastic process** $1+2\to 1+2$, consider the transitions of state:

$\alpha(p_1,p_2)\to\beta(q_1,q_2)$

$\alpha(p_1,p_2)\to\gamma_{\mathrm{el}}(k_1,k_2)$

$\beta(q_1,q_2)\to\gamma_{\mathrm{el}}(k_1,k_2)$



Since $\mathcal{M}_{\alpha\to\beta} = \mathcal{M}^*_{\beta\to\alpha} = \mathcal{M}_{\text{el}}(\cos\theta_{\alpha\beta})$, the unitarity condition becomes

$$\begin{aligned} & 2\,\text{Im}\,\mathcal{M}_{\text{el}}(\cos\theta_{\alpha\beta}) \\ = & \int d\Pi_{\gamma_{\text{el}}}\mathcal{M}^*_{\beta\to\gamma_{\text{el}}}\mathcal{M}_{\alpha\to\gamma_{\text{el}}}(2\pi)^4\delta^{(4)}(p_\alpha - p_{\gamma_{\text{el}}}) + \text{ inelastic terms} \\ \geq & \frac{\beta_1}{32\pi^2}\int d\Omega_{k_1}\mathcal{M}^*_{\text{el}}(\cos\theta_{\beta\gamma})\mathcal{M}_{\text{el}}(\cos\theta_{\alpha\gamma}), \end{aligned}$$

where $\beta_1 \equiv \sqrt{1-4m_1^2/s}$ and $d\Omega_{k_1} = d\phi_{k_1} d\cos\theta_{\alpha\gamma}$.

In terms of **partial waves**:

$$\begin{aligned} \text{Im}\,a_j^{\text{el}} \geq & \frac{\beta_1}{8\pi}\sum_{k,l}(2k+1)(2l+1)a_k^{\text{el}*}a_l^{\text{el}}\int d\cos\theta_{\alpha\beta}d\Omega_{k_1} \\ & \times P_j(\cos\theta_{\alpha\beta})P_k(\cos\theta_{\beta\gamma})P_l(\cos\theta_{\alpha\gamma}) \end{aligned}$$

The **addition theorem** for Legendre polynomials:

$$P_k(\cos\theta_{\beta\gamma}) = P_k(\cos\theta_{\alpha\beta})P_k(\cos\theta_{\alpha\gamma}) + 2\sum_{m=1}^{l} \frac{(l-m)!}{(l+m)!} P_k^m(\cos\theta_{\alpha\beta})P_k^m(\cos\theta_{\alpha\gamma})\cos m\phi_{k_1}$$

Carrying out all the integrations, we have

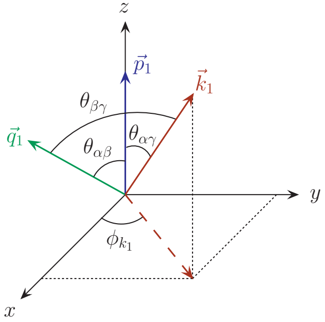
$$\mathrm{Im}\, a_j^{\mathrm{el}} \geq \beta_1 |a_j^{\mathrm{el}}|^2,$$

which is equivalent to

$$(\mathrm{Re}\, a_j^{\mathrm{el}})^2 + \left(\mathrm{Im}\, a_j^{\mathrm{el}} - \frac{1}{2\beta_1}\right)^2 \leq \frac{1}{(2\beta_1)^2}.$$

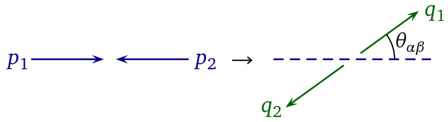
For the scattering of massless particles, $\beta_1 = 1$, and it implies

$$\left|\mathrm{Re}\, a_j^{\mathrm{el}}\right| \leq \frac{1}{2}, \quad \forall j.$$

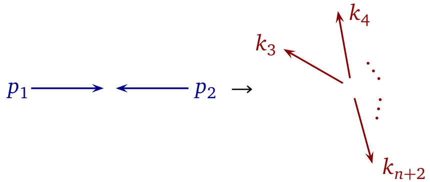


For $2 \to n$ **inelastic scattering**, consider the transitions of state:

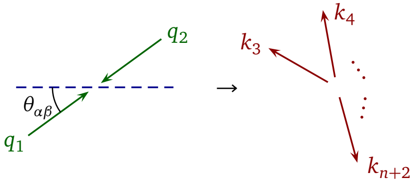
$$\alpha(p_1, p_2) \to \beta(q_1, q_2)$$



$$\alpha(p_1, p_2) \to \gamma_n(k_3, \cdots, k_{n+2})$$



$$\beta(q_1, q_2) \to \gamma_n(k_3, \cdots, k_{n+2})$$



The unitarity condition becomes

$$
\begin{aligned}
2\,\mathrm{Im}\,\mathcal{M}_{\mathrm{el}}(\cos\theta_{\alpha\beta}) &= \int d\Pi_{\gamma_{\mathrm{el}}}\mathcal{M}^*_{\beta\to\gamma_{\mathrm{el}}}\mathcal{M}_{\alpha\to\gamma_{\mathrm{el}}}(2\pi)^4\delta^{(4)}(p_\alpha - p_{\gamma_{\mathrm{el}}}) \\
&\quad + \int d\Pi_{\gamma_n}\mathcal{M}^*_{\beta\to\gamma_n}\mathcal{M}_{\alpha\to\gamma_n}(2\pi)^4\delta^{(4)}(p_\alpha - p_{\gamma_n}) + \text{ other inelastic terms} \\
&\geq \frac{\beta_1}{32\pi^2}\int d\Omega_{k_1}\mathcal{M}^*_{\mathrm{el}}(\cos\theta_{\beta\gamma})\mathcal{M}_{\mathrm{el}}(\cos\theta_{\alpha\gamma}) + \int d\Pi_{\gamma_n}\mathcal{M}^*_{\beta\to\gamma_n}\mathcal{M}_{\alpha\to\gamma_n}(2\pi)^4\delta^{(4)}(p_\alpha - p_{\gamma_n}).
\end{aligned}
$$

Introducing a new quantity

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

we have $\mathrm{Im}\,a_j^{\mathrm{el}} \geq \beta_1|a_j^{\mathrm{el}}|^2 + |b_j^{\mathrm{inel}}|^2$. Thus

$$|b_j^{\mathrm{inel}}|^2 \leq \frac{1}{4\beta_1} - \beta_1\left[(\mathrm{Re}\,a_j^{\mathrm{el}})^2 + \left(\mathrm{Im}\,a_j^{\mathrm{el}} - \frac{1}{2\beta_1}\right)^2\right] \leq \frac{1}{4\beta_1}.$$

For massless incoming particles,

$$\left|b_j^{\mathrm{inel}}\right| \leq \frac{1}{2}, \quad \forall j.$$