# Mono-$\gamma$ Production of a Vector Dark Matter at Future $e^+e^-$ Collider

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# Effective Operatros

For a vector field with mass $m_X$,

$$\mathcal{L}_X = -\frac{1}{4}X^{\mu\nu}X_{\mu\nu} + \frac{1}{2}m_X^2 X^\mu X_\mu \,. \quad (1)$$

Up to dimension 5 we have,

$$\mathcal{O}_1 = e\epsilon\,\overline{\psi}\gamma^\mu\psi X_\mu \,. \quad (2)$$

$$\mathcal{O}_2 = \frac{1}{2\Lambda_2}\overline{\psi}\sigma^{\mu\nu}\psi X_{\mu\nu}\,, \quad (3)$$

where $\psi$ is a charged fermion in the SM, and $\Lambda_2$ is the energy scale parameter.

$$\mathcal{O}_3 = \frac{1}{\Lambda_3^2} Z_{\mu\alpha}\mathcal{F}^{\alpha\nu}X^\mu{}_\nu\,, \quad (4)$$

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For anomalous triangle diagram we refer to arXiv:1705.06726.

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# Decay Properties

$$\Gamma_1(X \to \ell^+\ell^-) = \frac{m_X e^2 \epsilon^2}{12\pi}\left(1 + 2r_\ell^2\right)\sqrt{1 - 4r_\ell^2}\,, \quad m_X > m_\ell\,, \tag{8}$$

$$\Gamma_2(X \to \ell^+\ell^-) = \frac{m_X^3}{24\pi\Lambda_2^2}\left(1 + 8r_\ell^2\right)\sqrt{1 - 4r_\ell^2}\,, \quad m_X > m_\ell\,, \tag{9}$$

$$\Gamma_{3(4)}(Z \to X\gamma) = \frac{m_Z^5}{144\pi\Lambda_{3(4)}^4}\left(1 + r_X^2\right)\left(1 - r_X^2\right)^3, \quad m_X < m_Z\,, \tag{10}$$

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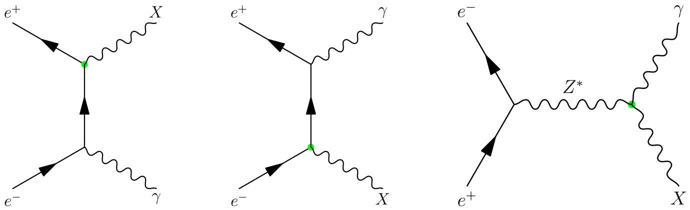
where $r_\ell = m_\ell/m_X$, $r_X = m_X/m_Z$, $r_Z = m_Z/m_X$.

# Mono-$\gamma$ Production: (Differential) Cross Section



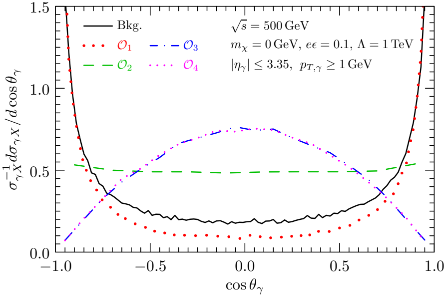

$$\frac{d\sigma_{1,\pm\mp}}{d\cos\theta_\gamma} = \frac{e^2\epsilon^2}{4\pi s\left(1-z_X^2\right)\sin^2\theta_\gamma}\left[\left(1+z_X^4\right)\left(1+\cos^2\theta_\gamma\right)+2z_X^2\sin\theta_\gamma^2\right], \tag{12}$$

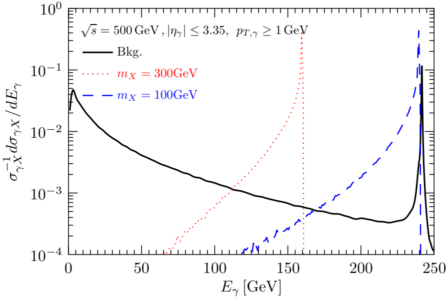
$$\frac{d\sigma_{2,\pm\pm}}{d\cos\theta_\gamma} = \frac{1}{\pi\Lambda_2^2\left(1-z_X^2\right)}\left[\left(1-z_X^2\right)^2+2z_X^4+z_X^2\left(1+z_X^4\right)\cot\theta_\gamma^2\right], \tag{13}$$

$$\frac{d\sigma_{3(4),\pm\mp}}{d\cos\theta_\gamma} = \frac{e^2\left(g_V\mp g_A\right)^2 s\left(1-z_X^2\right)^3}{64\pi\Lambda_{3(4)}^4\left[\left(1-z_Z^2\right)^2+z_Z^4y_Z^2\right]}\left[\sin^2\theta_\gamma+\frac{1}{2}z_Z^2\left(1+\cos^2\theta_\gamma\right)\right], \tag{14}$$

# Mono-$\gamma$ Production: (Differential) Cross Section

$$E_\gamma = \frac{1}{2}\sqrt{s}\left(1 - \frac{m_X^2}{s}\right)$$




$$\frac{d\sigma_{1,\pm\mp}}{d\cos\theta_\gamma} = \frac{e^2\epsilon^2}{4\pi s(1-z_X^2)\sin^2\theta_\gamma}\left[\left(1+z_X^4\right)\left(1+\cos^2\theta_\gamma\right) + 2z_X^2\sin\theta_\gamma^2\right], \quad (12)$$

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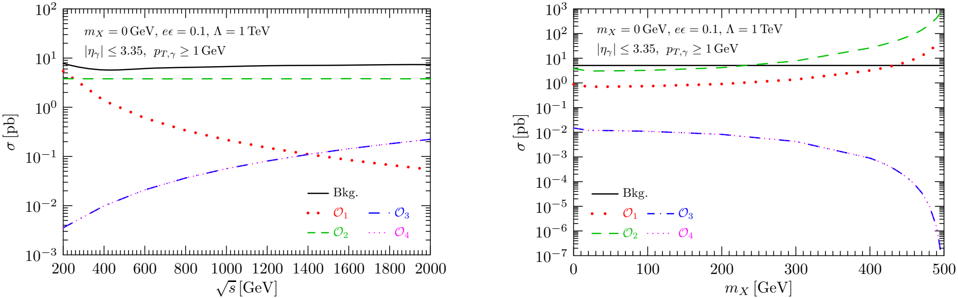


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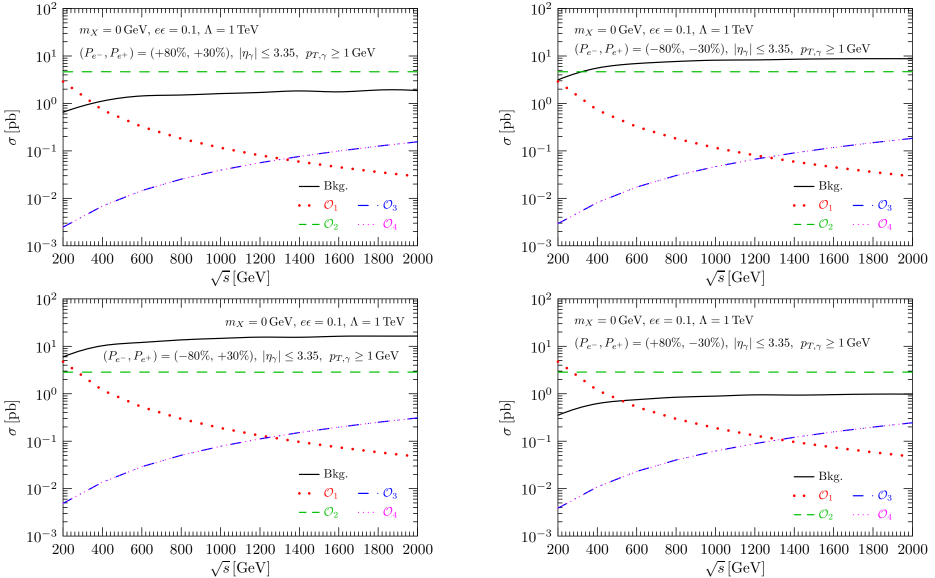
# *Mono-γ Production: Beam Polarization*



# Constraints & Prospects

**BaBar @** $\sqrt{s} = 10.58\,GeV$, with following cuts,

$$-0.4 < \cos\theta_\gamma < 0.6 \qquad \text{for} \quad m_\chi < 5.5\,GeV\,, \tag{15}$$

$$-0.6 < \cos\theta_\gamma < 0.6 \qquad \text{for} \quad m_\chi > 5.5\,GeV\,, \tag{16}$$

we have

$$\Lambda_i \geq \left[\frac{\sigma_i(\Lambda_i = 1GeV, m_\chi = m_\chi^{BarBar})}{\sigma_1(\epsilon = \epsilon_{BarBar}, m_\chi = m_\chi^{BarBar})}\right]^{1/\kappa} [GeV]\,. \tag{17}$$

**DELPHE @** $\sqrt{s} \in [180.8, 209.2]\,GeV$

$$45^\circ < \theta_\gamma < 135^\circ\,, \quad 0.06\,E_{Beam} < E_\gamma < 1.1E_{Beam}\,, \tag{18}$$

Experimental significances are estimated by following $\chi^2$-function,

$$\chi^2 = \sum_{i,j}\left[\frac{N_{Sig}(\sqrt{s_i}, \bar{\theta}_j)}{\sqrt{N_{Bkg+Sig}(\sqrt{s_i}, \bar{\theta}_j) + \Delta\sigma^2_{Syst}\cdot N^2_{Bkg}(\sqrt{s_i}, \bar{\theta}_j)}}\right]^2, \tag{19}$$

# Constraints & Prospects

At future $e^+e^-$ colliders, experimental significances are estimated by following $\chi^2$-function, with $\epsilon_{ISR} = 70\%$ and $\epsilon_{Syst} = 70\%$,

$$\chi^2 = \sum_i \frac{\left(\epsilon_{ISR} \cdot \mathcal{N}_i^{Sig}\right)^2}{\mathcal{N}_i^{Bkg} + \epsilon_{ISR} \cdot \mathcal{N}_i^{Sig} + \left(\epsilon_{Syst} \cdot \mathcal{N}_i^{Bkg}\right)^2}, \tag{15}$$

For CEPC ($\sqrt{s} = 240\,GeV$, $\mathcal{L} = 5.6\ ab^{-1}$), following kinematical cuts are employed,

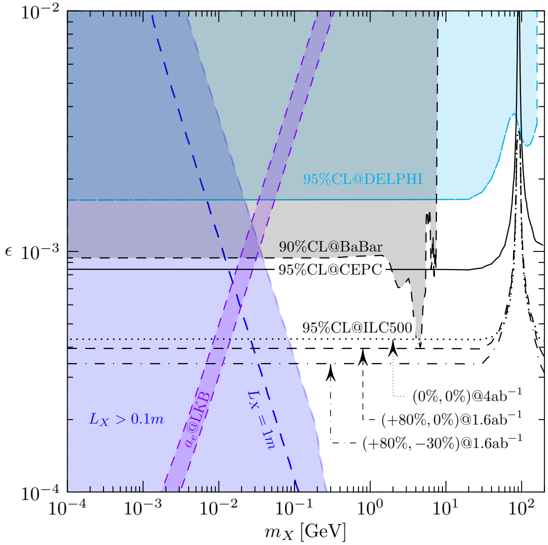
$$p_{T,\gamma} > 0.5\,GeV\,, \quad |\eta_\gamma| < 2.65\,. \tag{16}$$

For ILC, we use following kinematical cuts are and three polarization configurations,

| $(\mathcal{P}_{e^-}, \mathcal{P}_{e^+})$ | (0, 0) | (+80%, 0) | (+80%, -30%) |
|---|---|---|---|
| $\mathcal{L}_{Int.}\ \left[ab^{-1}\right]$ | 4 | 1.6 | 1.6 |

$$p_{T,\gamma} > 6\,GeV\,, \quad |\eta_\gamma| < 2.79\,. \tag{17}$$

# *Constraints & Prospects*



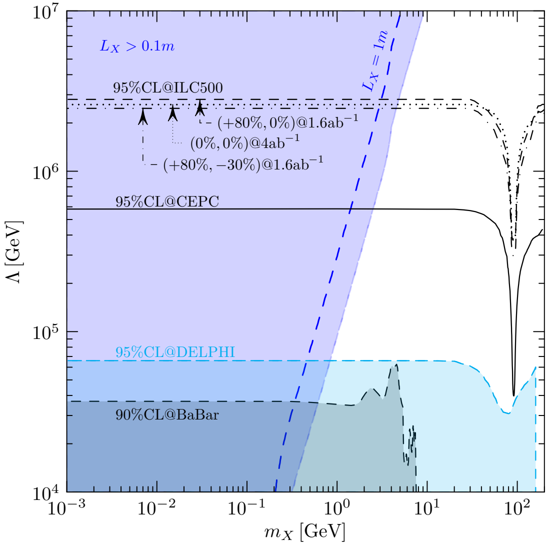

$$\mathcal{O}_1 = e\epsilon\,\overline{\psi}\gamma^\mu\psi X_\mu$$

- **Blue region**:

$$\mathcal{L}_X = \gamma_X\tau_X = \frac{\sqrt{s}}{2m_X\Gamma_X}\left(1 + \frac{m_X^2}{s}\right) > 0.1m.$$

- Blue line: $\mathcal{L}_X = 1m$.
- Purple region: $a_e < 1\sigma$ [LKB2020].
- Gray region: 90% exclusion line **@BaBar**, with total luminosity $53\,fb^{-1}$.
- Cyan region: 95% exclusion line **@DELPHI**,

# Constraints & Prospects

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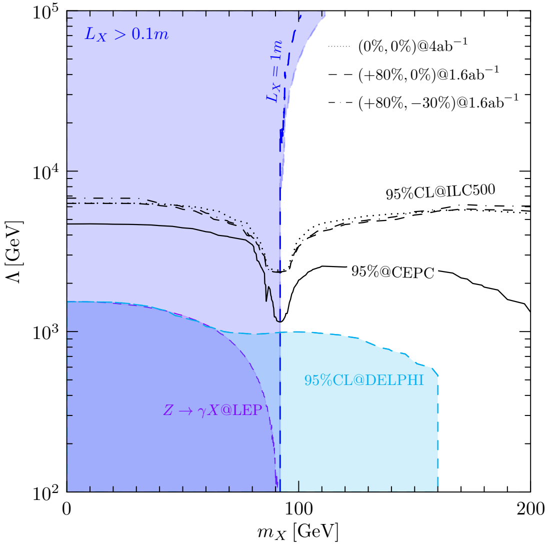


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- Purple region: $\mathcal{B}_{Z\to X\gamma} < 10^{-6}$ **@LEP**,
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Thank you.