Implications for the Vacuum Magnetic Birefringence Experiment from the Parity Violating Interactions between Fermionic Dark Matter and Extra U(1) Mediator

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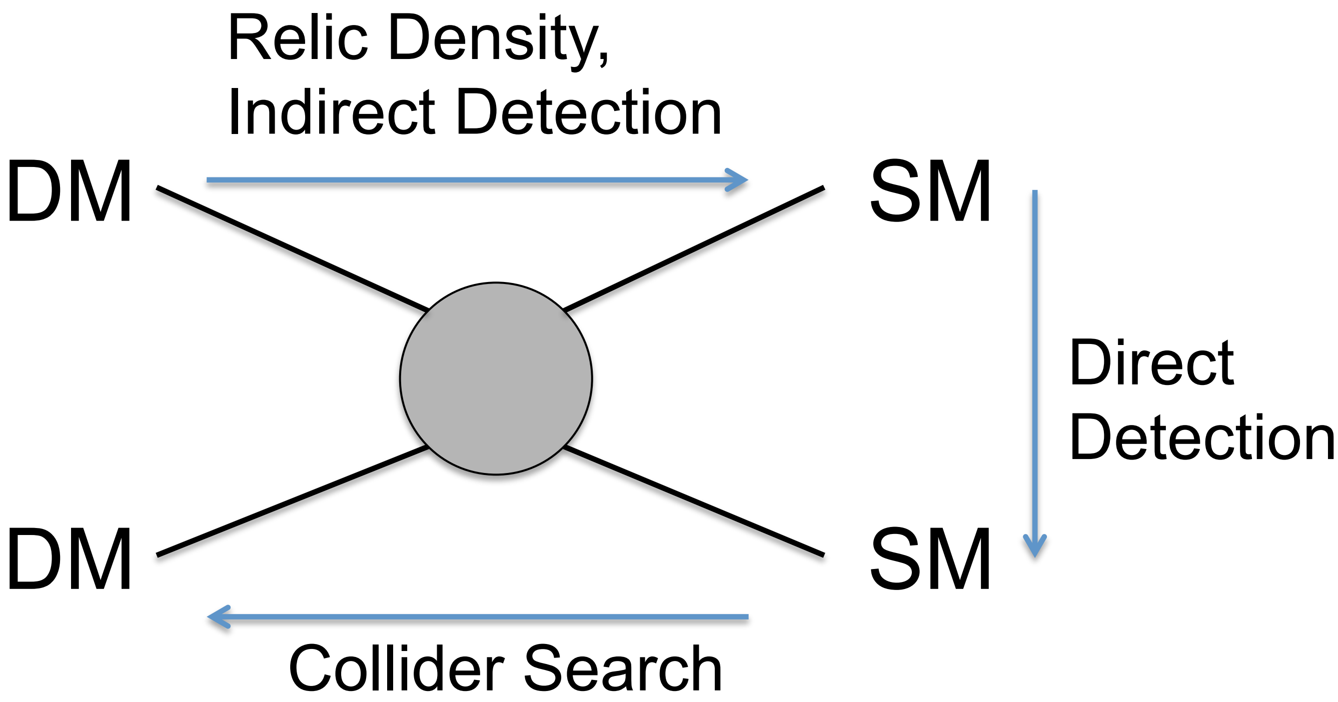
KAIST, Daejeon

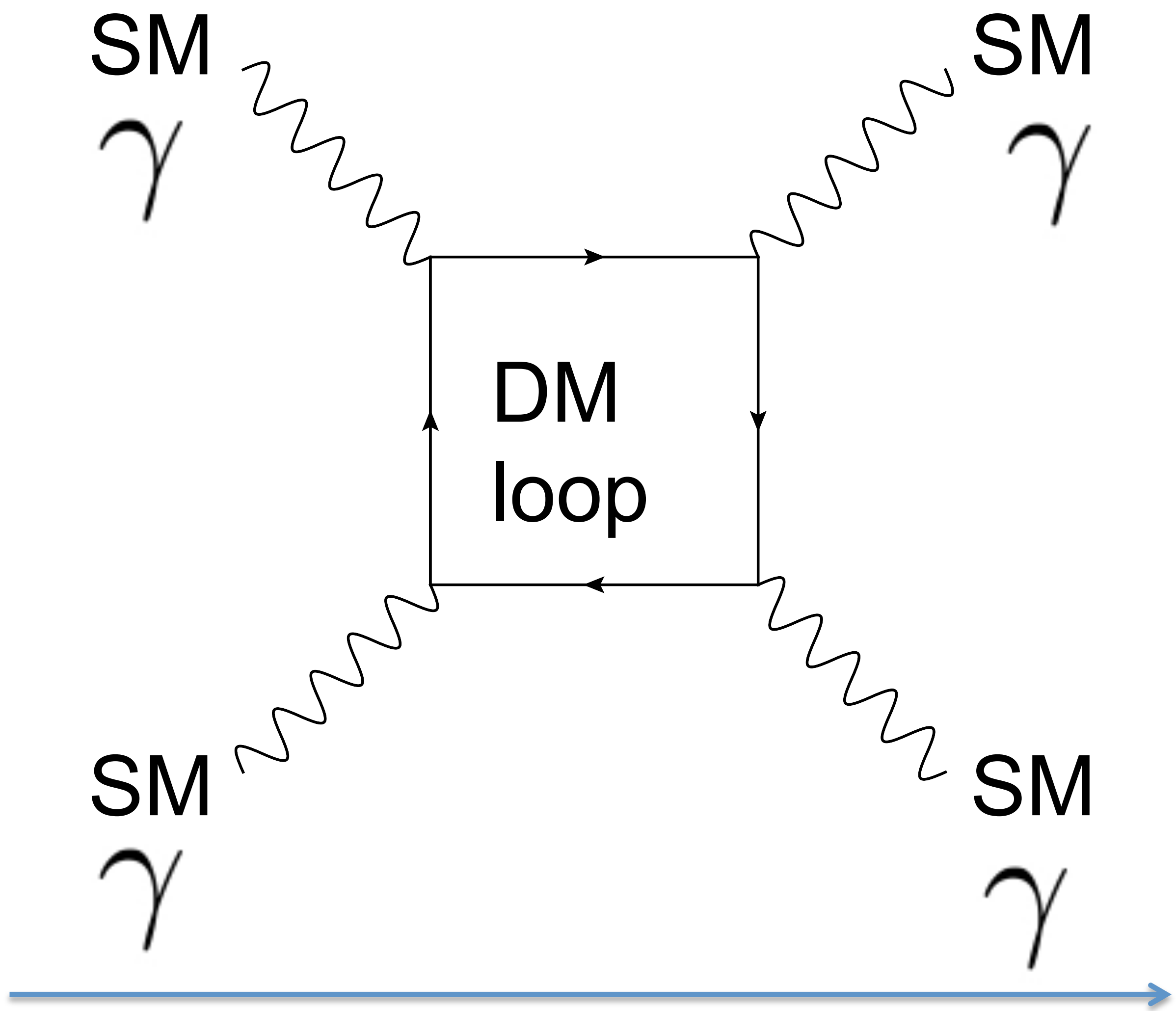
Dark Matter Search



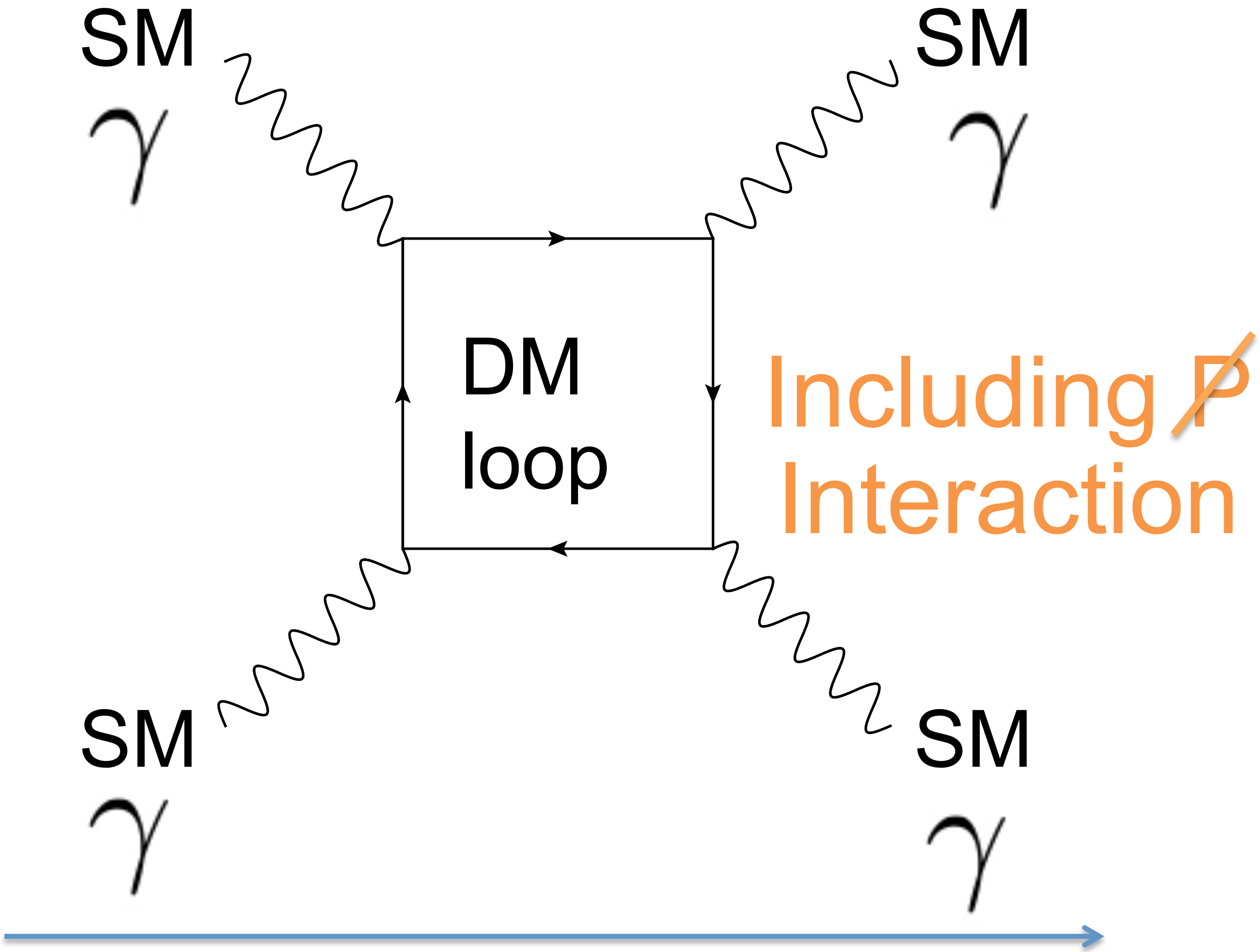
In this talk: Another search

1-loop effect

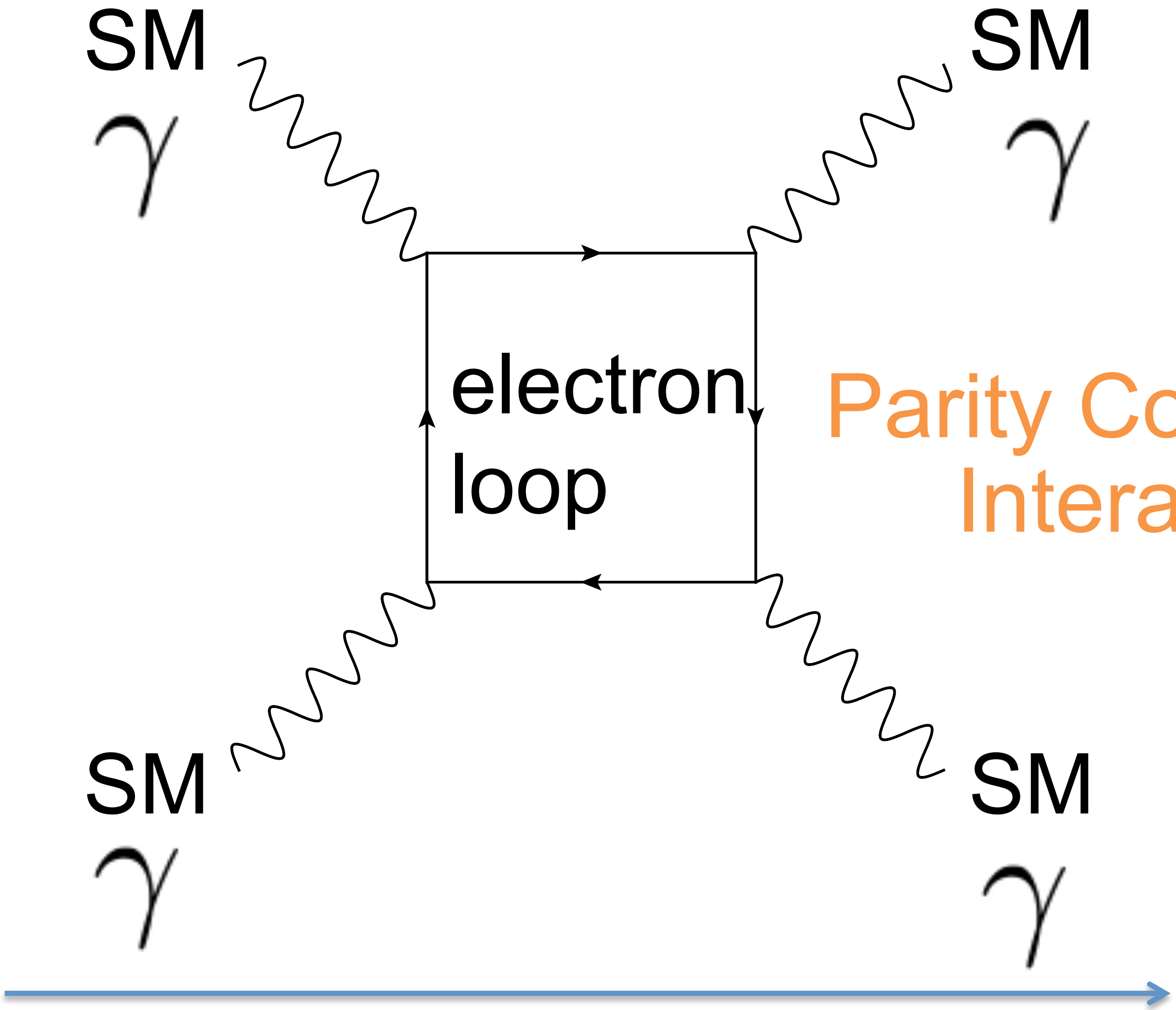
Dark Matter Search



Dark Matter Search



QED Case



Parity Conserving Interaction

QED Case

W. Heisenberg, H. Euler, Z. Phys. **98**, 714 (1936)

Heisenberg-Euler Lagrangian:

$$\mathfrak{L} = -\mathfrak{F} - \frac{1}{8\pi^2}\int_0^\infty ds\, s^{-3}\exp(-m^2 s)$$

$$\times\left[(es)^2\mathfrak{G}\frac{\mathrm{Re}\cosh esX}{\mathrm{Im}\cosh esX} - 1 - \tfrac{2}{3}(es)^2\mathfrak{F}\right]$$

$$\mathcal{F} = \frac{1}{4}F_{\mu\nu}F^{\mu\nu} = \frac{1}{2}\left(\vec{B}^2 - \vec{E}^2\right)$$

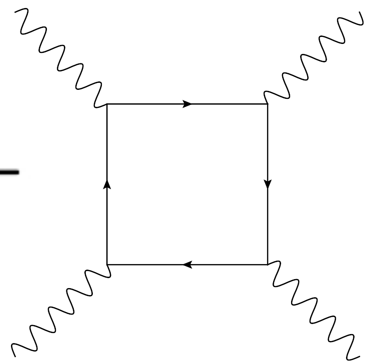
$$\mathcal{G} = \frac{1}{4}F_{\mu\nu}\tilde{F}^{\mu\nu} = \vec{E}\cdot\vec{B}$$

$$= \tfrac{1}{2}(\mathbf{E}^2 - \mathbf{H}^2) + \frac{2\alpha^2}{45}\frac{(\hbar/mc)^3}{mc^2}$$

$$\times[(\mathbf{E}^2 - \mathbf{H}^2)^2 + 7(\mathbf{E}\cdot\mathbf{H})^2] + \cdots.$$

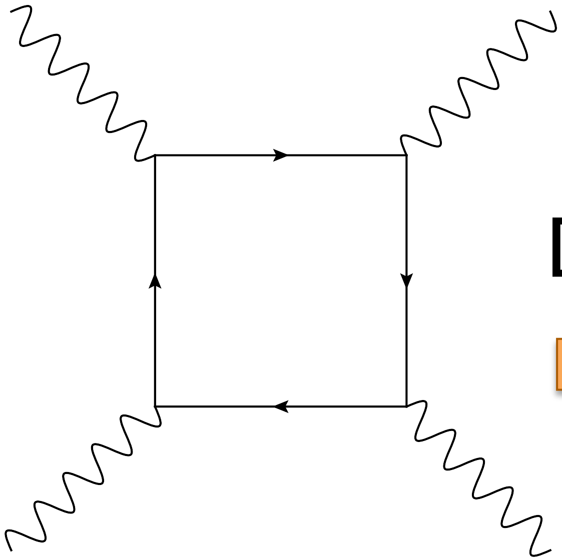
from J. Schwinger, Phys. Rev. **82**, 664 (1951)

$$\mathcal{L}_{\mathrm{eff}} = -\frac{1}{4}F_{\mu\nu}^2 +$$

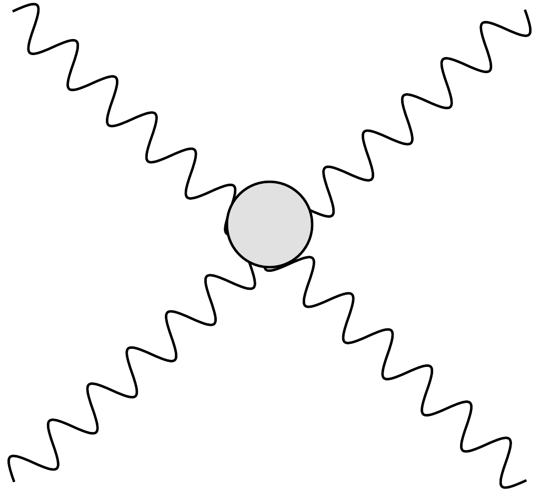


$$+ \cdots \; !$$

Dark Matter Case



Photon Energy
^
^
Dark Matter Mass



$$\mathcal{L}_{\text{eff}} = -\mathcal{F} + \boxed{a\mathcal{F}^2 + b\mathcal{G}^2 + ic\mathcal{F}\mathcal{G}}$$

$$\mathcal{F} = \frac{1}{4}F_{\mu\nu}F^{\mu\nu} = \frac{1}{2}\left(\vec{B}^2 - \vec{E}^2\right) \qquad \mathcal{G} = \frac{1}{4}F_{\mu\nu}\tilde{F}^{\mu\nu} = \vec{E}\cdot\vec{B}$$

Dark Matter Case

$$S_\psi(m) = \int d^4x\ \bar{\psi}_{\rm DM}\left[\gamma^\mu\left(i\partial_\mu - (g_V + g_A\gamma_5)A'_\mu\right) - m\right]\psi_{\rm DM}$$

$$\mathcal{L}_{\rm eff} = -\mathcal{F} + \boxed{a\mathcal{F}^2 + b\mathcal{G}^2 + ic\mathcal{F}\mathcal{G}}$$

$$\mathcal{F} = \frac{1}{4}F_{\mu\nu}F^{\mu\nu} = \frac{1}{2}\left(\vec{B}^2 - \vec{E}^2\right)\quad \mathcal{G} = \frac{1}{4}F_{\mu\nu}\tilde{F}^{\mu\nu} = \vec{E}\cdot\vec{B}$$

$$a = \frac{1}{(4\pi)^2 m^4}\left(\frac{8}{45}\ g_V^4 - \frac{4}{5}\ g_V^2 g_A^2 - \frac{1}{45}\ g_A^4\right)$$

$$b = \frac{1}{(4\pi)^2 m^4}\left(\frac{14}{45}\ g_V^4 + \frac{34}{15}\ g_V^2 g_A^2 + \frac{97}{90}\ g_A^4\right)$$

$$c = \frac{1}{(4\pi)^2 m^4}\left(\frac{4}{3}\ g_V^3 g_A + \frac{28}{9}\ g_V g_A^3\right)$$

We follow a method developed by Schwinger J. Schwinger, Phys. Rev.**82**, 664 (1951)

$$\varepsilon \equiv \frac{g_1 Y_s}{g_1' Y_s'}$$

Dark Matter Model

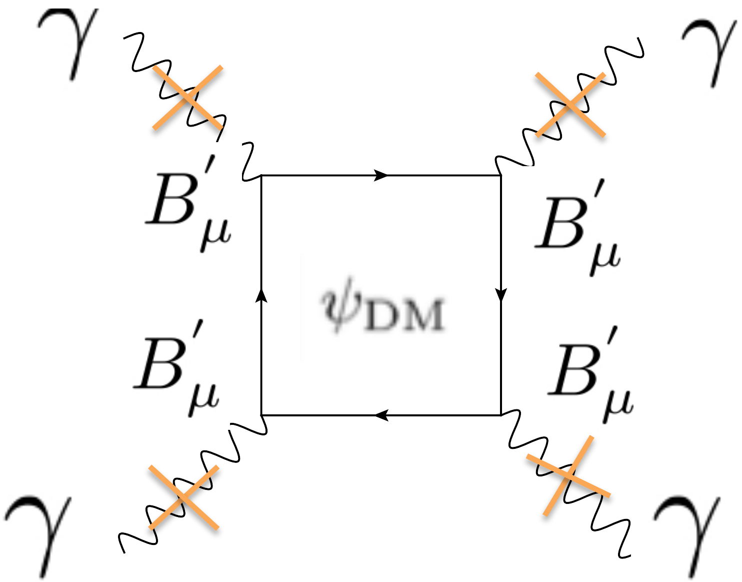
$$\boxed{\gamma}\ \tilde{A}_\mu = \frac{g_1 A^3_\mu + g_2 B_\mu}{\sqrt{g_1^2+g_2^2}} - \underbrace{\varepsilon \frac{g_2}{\sqrt{g_1^2+g_2^2}}}_{=\chi} B'_\mu$$

We assume

$$\epsilon \ll 1$$

$$\mathcal{L}'_{\mathrm{eff}} = \chi^4 \left\{ a\, \mathcal{F}^2 + b\, \mathcal{G}^2 + ic\, \mathcal{F}\mathcal{G} \right\}$$

$$S_\psi(m) = \int d^4x\ \bar{\psi}_{\mathrm{DM}} \left[\gamma^\mu \left(i\partial_\mu - (g_V + g_A \gamma_5)\, B'_\mu \right) - m \right] \psi_{\mathrm{DM}}$$



Vacuum Magnetic Birefringence Experiment

arXiv:1705.00495

- OVAL (Observing Vacuum with Laser) experiment

Conventional

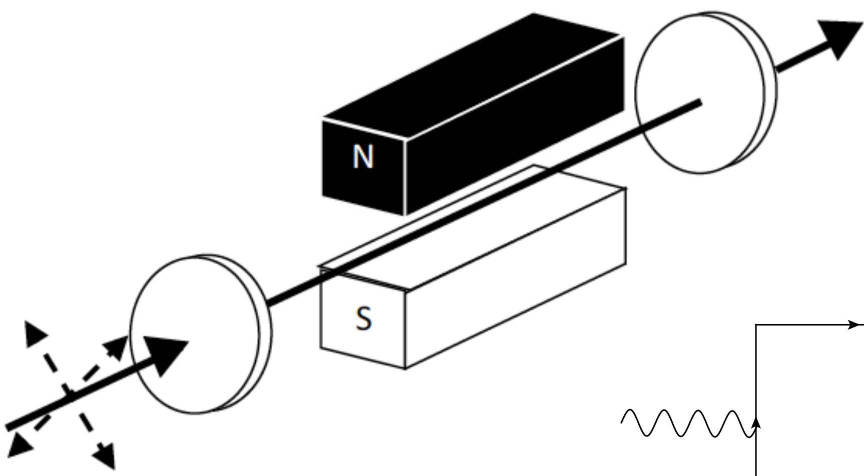
Eur. Phys. J. D (2014) **68**: 16

- BMV experiment

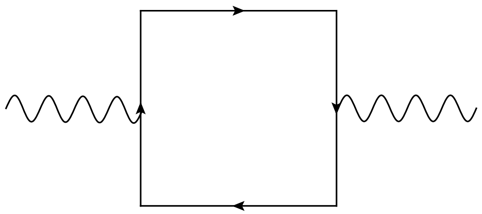
Eur. Phys. J. C (2016) **76**: 24

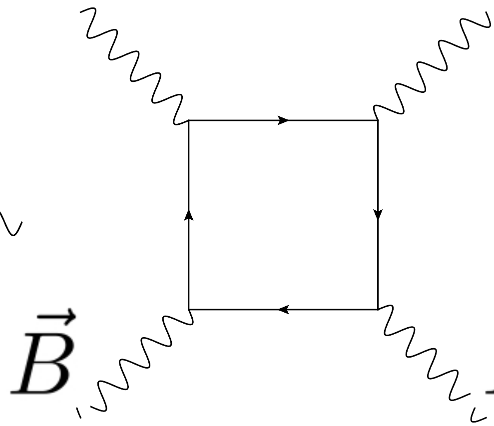
- PVLAS experiment

$\boldsymbol{\varepsilon}_f = \frac{1}{\sqrt{2}}\begin{pmatrix}1\\-1\\0\end{pmatrix}$ or $\frac{1}{\sqrt{2}}\begin{pmatrix}1\\1\\0\end{pmatrix}$



$\boldsymbol{\varepsilon}_i = \frac{1}{\sqrt{2}}\begin{pmatrix}1\\1\\0\end{pmatrix}$ or $\frac{1}{\sqrt{2}}\begin{pmatrix}1\\-1\\0\end{pmatrix}$

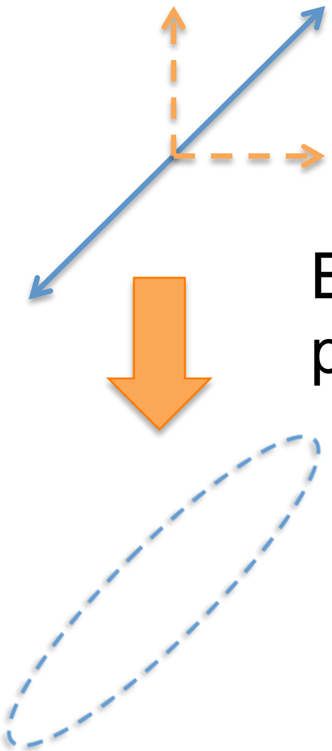




Vacuum Magnetic Birefringence Experiment

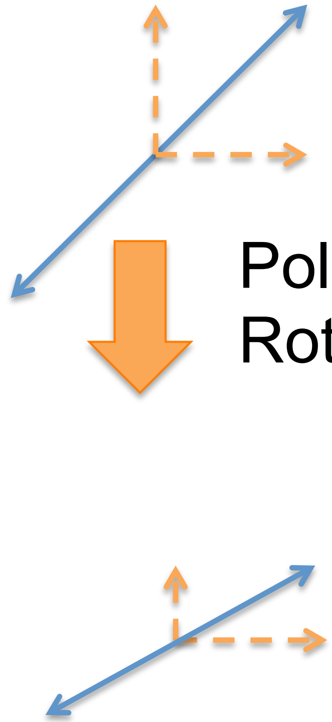
Polarization State: 2 parameters

Ellipticity



Elliptically polarized

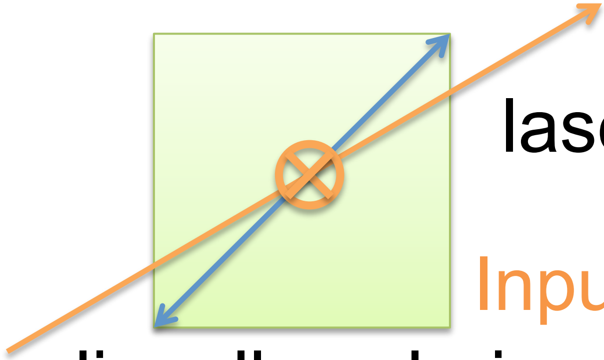
Direction of the long axis of an ellipse



Polarization Rotation

Vacuum Magnetic Birefringence Experiment

Conventional

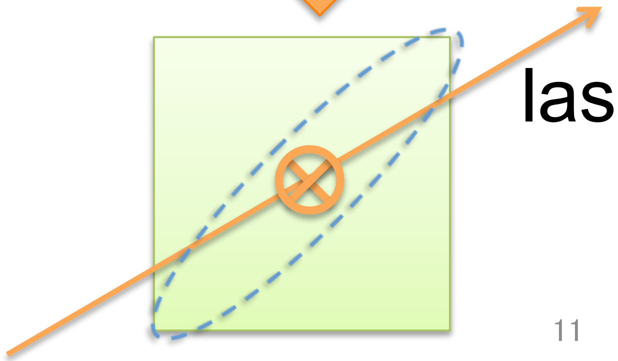


lineally polarized

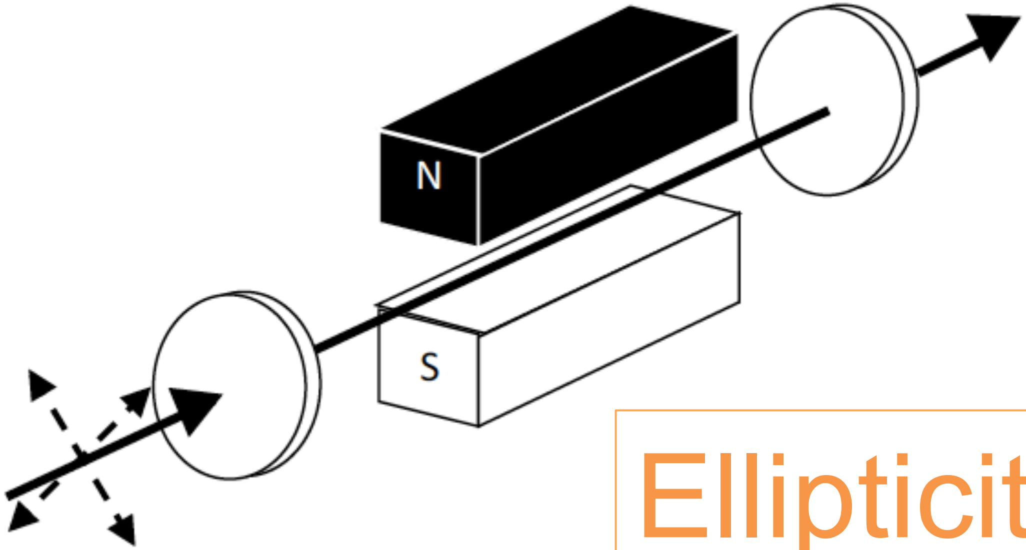
Magnetic Field

Elliptically polarized

Output



$$\boldsymbol{\varepsilon}_f = \frac{1}{\sqrt{2}}\begin{pmatrix}1\\-1\\0\end{pmatrix} \text{or } \frac{1}{\sqrt{2}}\begin{pmatrix}1\\1\\0\end{pmatrix}$$



$$\boldsymbol{\varepsilon}_i = \frac{1}{\sqrt{2}}\begin{pmatrix}1\\1\\0\end{pmatrix} \text{ or } \frac{1}{\sqrt{2}}\begin{pmatrix}1\\-1\\0\end{pmatrix}$$

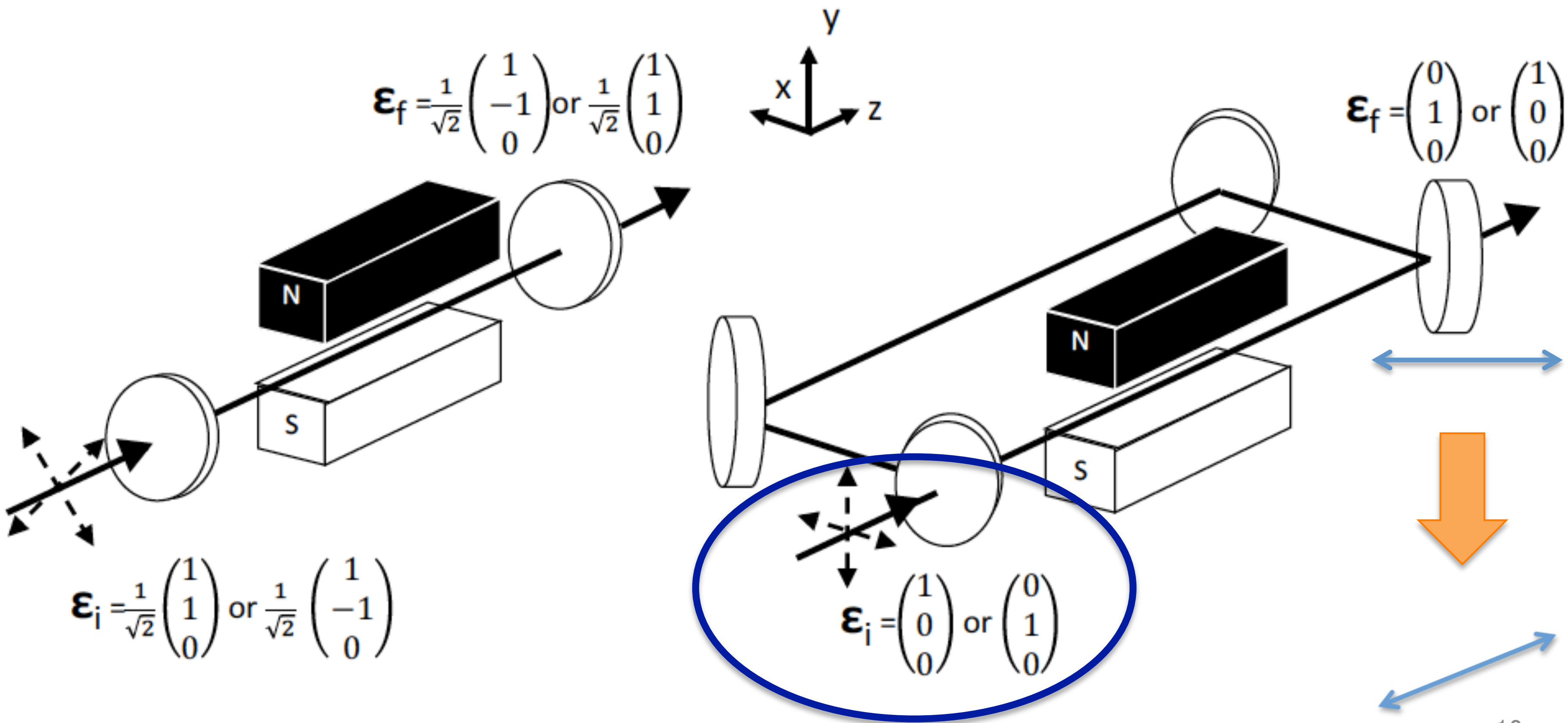
Ellipticity

Vacuum Magnetic Birefringence Experiment

Detecting ~~P~~ Interaction

Conventional

Ours

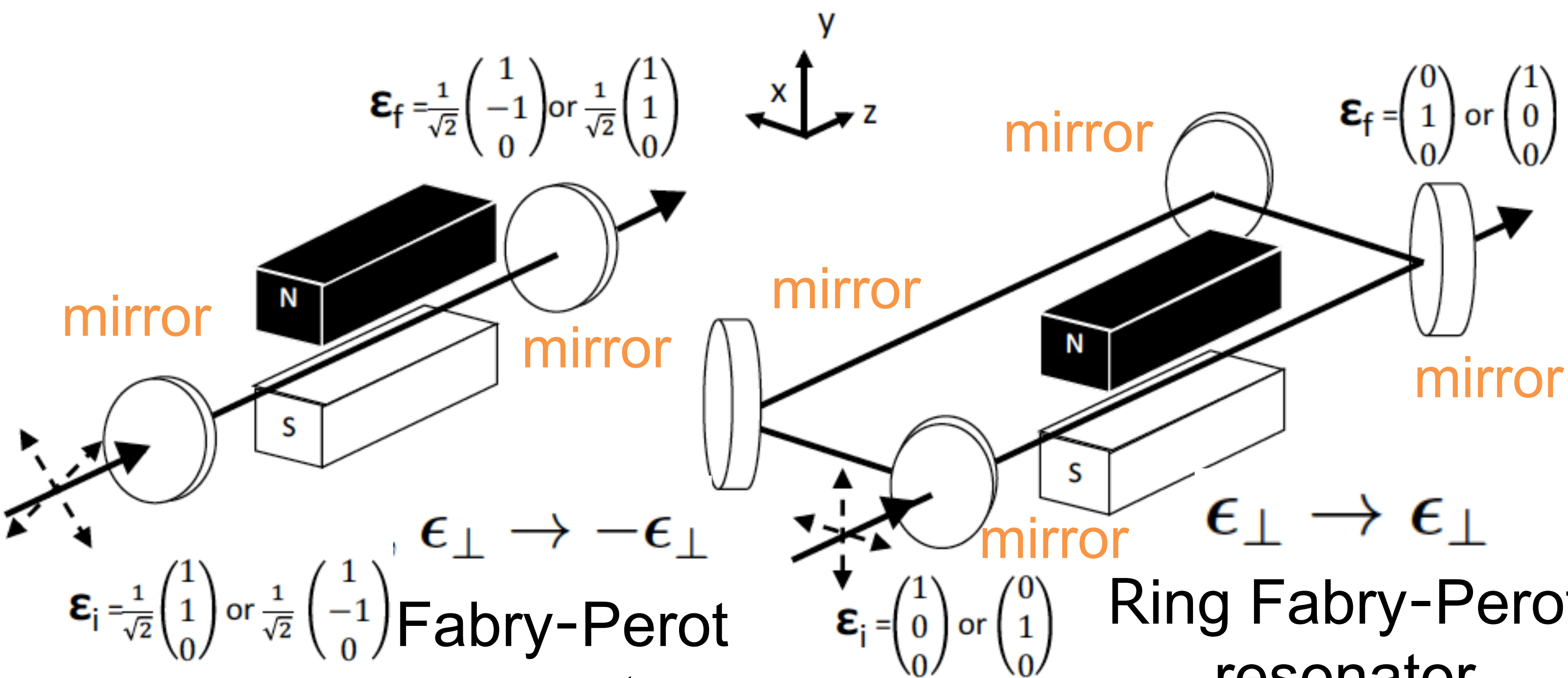


Vacuum Magnetic Birefringence Experiment

Detecting ~~P~~ Interaction

Conventional

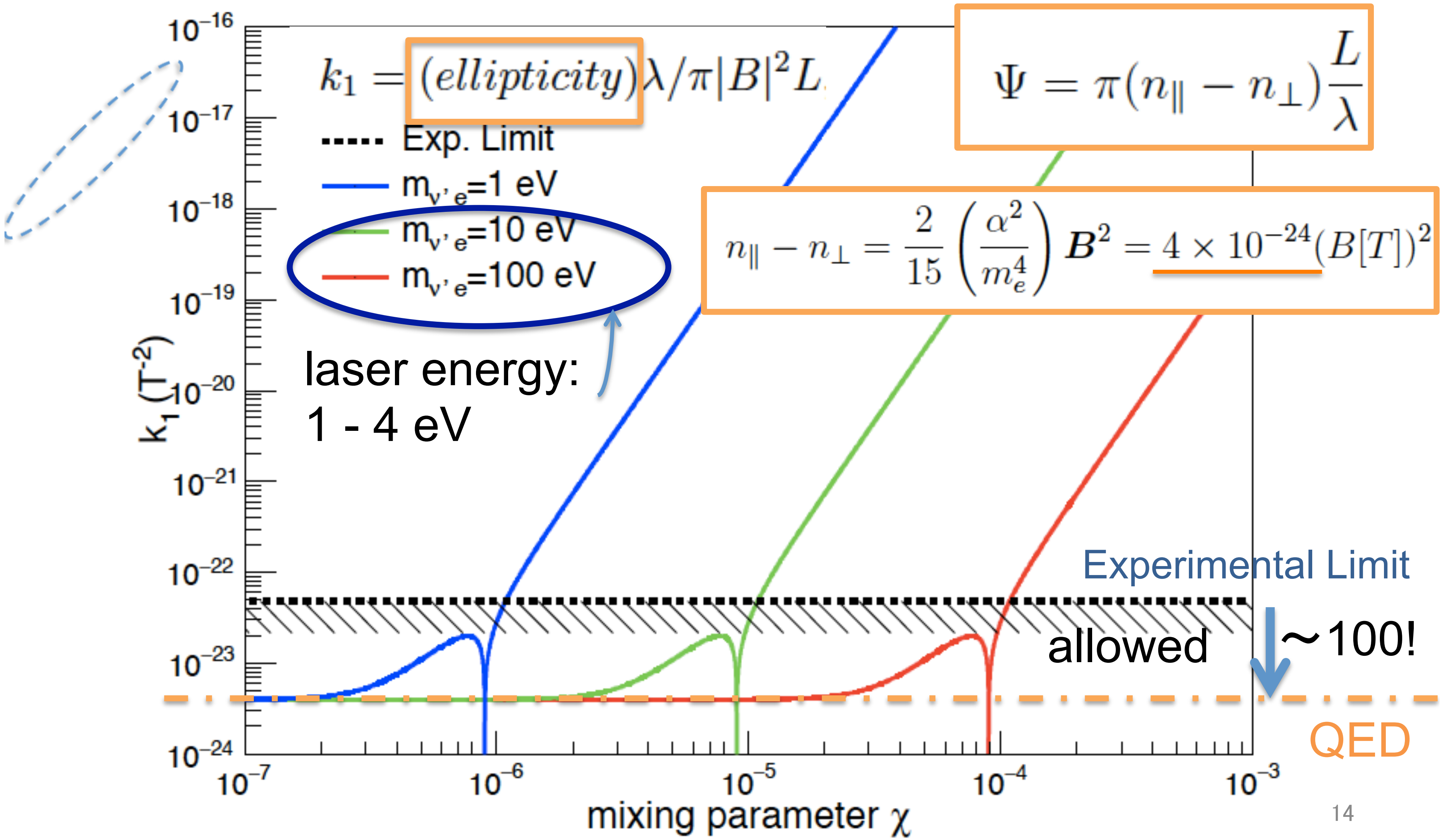
Ours



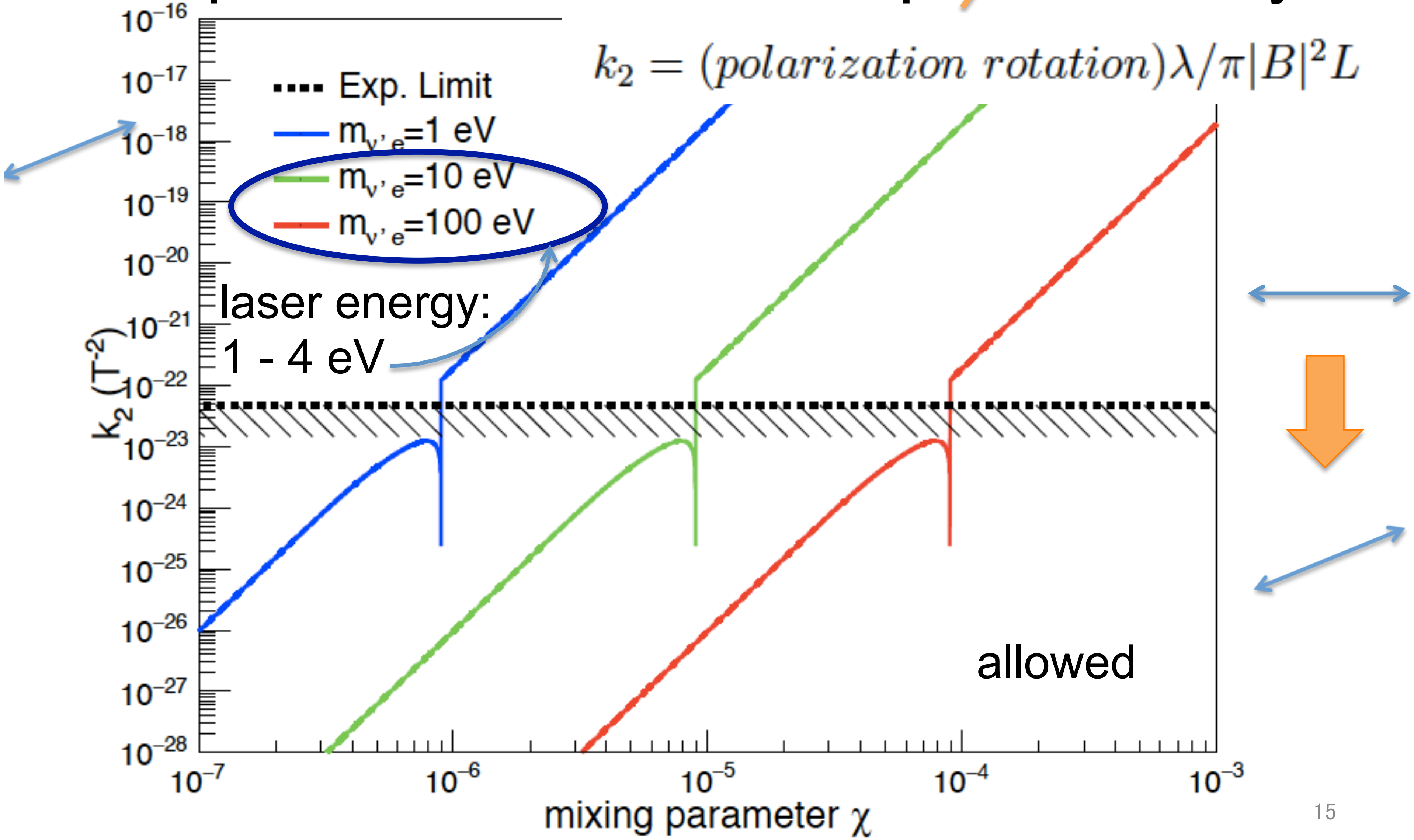
Fabry-Perot resonator

Ring Fabry-Perot resonator

Vacuum Magnetic Birefringence Experiment – Conventional, QED/DM



Vacuum Magnetic Birefringence Experiment – New Set Up, ~~P~~ DM only



Summary

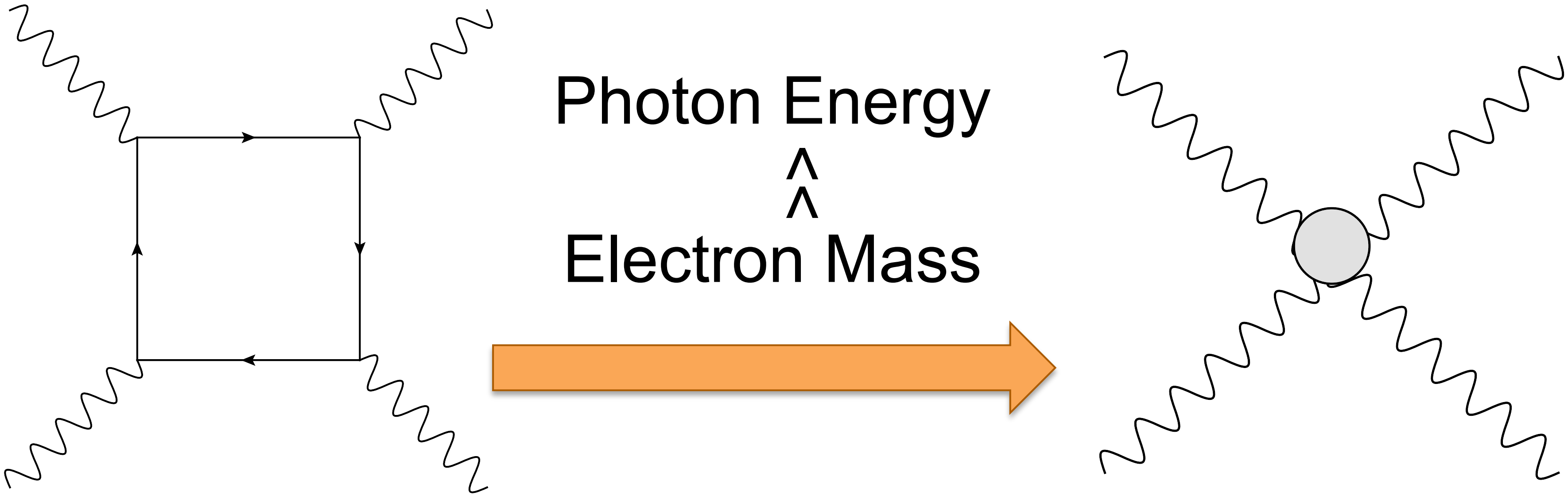
1. We considered Parity Violated Dark Matter Model, and calculated light-by-light scattering effective Lagrangian

We focus on Vacuum Magnetic Birefringence Experiment to probe the dark sector.

2. We propose new polarization state and the ring resonator in stead of the usual Fabry-Perot resonator to measure the Parity violated term

Backup

QED Case



$$\mathcal{L}_{\rm eff}^{\rm QED} = -\mathcal{F} + \boxed{\frac{8}{45}\left(\frac{\alpha^2}{m_e^4}\right)\mathcal{F}^2 + \frac{14}{45}\left(\frac{\alpha^2}{m_e^4}\right)\mathcal{G}^2} + \cdots ,$$

$$\mathcal{F} = \frac{1}{4}F_{\mu\nu}F^{\mu\nu} = \frac{1}{2}\left(\vec{B}^2 - \vec{E}^2\right) \qquad \mathcal{G} = \frac{1}{4}F_{\mu\nu}\tilde{F}^{\mu\nu} = \vec{E}\cdot\vec{B}$$

Dark Matter Model

SM + U'(1)$_{Y'}$ + 1 Complex Scalar

$$\mathcal{L}_S = \left| \left(i\partial_\mu - g_1 Y_s B_\mu - g_1' Y_s' B_\mu' \right) S(x) \right|^2$$

spontaneously broken $\langle S \rangle = v_s/\sqrt{2}$,

$$\mathcal{L}_{\text{mixing}} = \frac{1}{2} m_{B'}^2 \left(\varepsilon^2 B_\mu B^\mu + 2\varepsilon B_\mu B'^\mu + B'_\mu B'^\mu \right)$$

$$m_{B'} = g_1' Y_s' v_s \qquad \varepsilon \equiv \frac{g_1 Y_s}{g_1' Y_s'}$$

$$m_{B'} = g_1' Y_s' v_s$$

Dark Matter Model

$$\varepsilon \equiv \frac{g_1 Y_s}{g_1' Y_s'}$$

$$\mathcal{L}_{\rm mixing} = \frac{1}{2} m_{B'}^2 \left(\varepsilon^2 B_\mu B^\mu + 2\varepsilon B_\mu B'^\mu + B'_\mu B'^\mu \right)$$

mass diagonalization

$$(m_{\tilde{A}})^2 = 0,\ (m_{\tilde{Z}})^2 = \frac{1}{4} v^2 (g_1^2 + g_2^2) + \varepsilon^2 \frac{g_1^2}{g_1^2 + g_2^2 - \alpha'} (m_{B'})^2,\ \text{and}$$

$$(m_{\tilde{B}'})^2 = (m_{B'})^2 \left(1 + \varepsilon^2 \frac{g_2^2 - \alpha'}{g_1^2 + g_2^2 - \alpha'} \right).$$

$$\tilde{A}_\mu = \frac{g_1 A_\mu^3 + g_2 B_\mu}{\sqrt{g_1^2 + g_2^2}} - \varepsilon \frac{g_2}{\sqrt{g_1^2 + g_2^2}} B'_\mu$$

We assume $\epsilon \ll 1$

$$m_{B'} = g_1' Y_s' v_s$$

$$\varepsilon \equiv \frac{g_1 Y_s}{g_1' Y_s'}$$

Dark Matter Model

$$\mathcal{L}_{\text{mixing}} = \frac{1}{2} m_{B'}^2 \left(\varepsilon^2 B_\mu B^\mu + 2\varepsilon B_\mu B'^\mu + B'_\mu B'^\mu \right)$$

mass diagonalization

$$(m_{\tilde{A}})^2 = 0, \ (m_{\tilde{Z}})^2 = \frac{1}{4} v^2 (g_1^2 + g_2^2) + \varepsilon^2 \frac{g_1^2}{g_1^2 + g_2^2 - \alpha'} (m_{B'})^2, \ \text{and}$$

$$(m_{\tilde{B}'})^2 = (m_{B'})^2 \left(1 + \varepsilon^2 \frac{g_2^2 - \alpha'}{g_1^2 + g_2^2 - \alpha'} \right).$$

$$\tilde{A}_\mu = \frac{g_1 A_\mu^3 + g_2 B_\mu}{\sqrt{g_1^2 + g_2^2}} - \varepsilon \frac{g_2}{\sqrt{g_1^2 + g_2^2}} B'_\mu$$

We assume $\epsilon \ll 1$

Vacuum Magnetic Birefringence Experiment

$$\sin\phi = \frac{c}{\left\{\left((a-b)+\sqrt{(a-b)^2-c^2}\right)^2+c^2\right\}^{\frac{1}{2}}}$$

$$\cos\phi = \frac{(a-b)+\sqrt{(a-b)^2-c^2}}{\left\{\left((a-b)+\sqrt{(a-b)^2-c^2}\right)^2+c^2\right\}^{\frac{1}{2}}}$$

$$\cosh\theta = \frac{a-b}{\left(c^2-(a-b)^2\right)^{\frac{1}{2}}}$$

$$\sinh\theta = \frac{c}{\left(c^2-(a-b)^2\right)^{\frac{1}{2}}}$$

$$\Psi = \pi|B|^2\frac{L}{\lambda}\sqrt{|(a-b)^2-c^2|},$$

described by a,b,c,
B(magnetic field),
λ(laser beam wave length) ,
L(beam propagating distance with B)

Vacuum Magnetic Birefringence Experiment

0!

$$\epsilon_\parallel \;\to\; \begin{cases} \boxed{\left((-i\sin\Psi+\cos2\phi\cos\Psi)\epsilon_\parallel + \sin\Psi\sin2\phi\,\epsilon_\perp\right)/\cos2\phi \quad (D>0)} \\ (\cosh\Psi + i\sinh\theta\sinh\Psi)\epsilon_\parallel - \cosh\theta\sinh\Psi\,\epsilon_\perp \quad (D<0) \end{cases}$$

$$\epsilon_\perp \;\to\; \begin{cases} \boxed{\left(\sin2\phi\sin\Psi\,\epsilon_\parallel + (i\sin\Psi+\cos2\phi\cos\Psi)\epsilon_\perp\right)/\cos2\phi \quad (D>0)} \\ -\cosh\theta\sinh\Psi\,\epsilon_\parallel + (\cosh\Psi - i\sinh\theta\sinh\Psi)\epsilon_\perp \quad (D<0) \end{cases}$$

0 !

$$\phi = 0(\mathrm{QED})$$

$$\sinh\theta\sinh\Psi/(\cosh\Psi-\cosh\theta\sinh\Psi) \quad \text{for} \quad \epsilon_i=\epsilon(45^\circ)\ (D<0)$$

$$\boxed{\sin\Psi/\cos(\Psi-2\phi) \quad \text{for} \quad \epsilon_i=\epsilon(45^\circ)\ (D>0)}$$

tanΨ

Vacuum Magnetic Birefringence Experiment

$$\sin\phi = \frac{c}{\left\{\left((a-b)+\sqrt{(a-b)^2-c^2}\right)^2+c^2\right\}^{\frac{1}{2}}}$$

$$\cos\phi = \frac{(a-b)+\sqrt{(a-b)^2-c^2}}{\left\{\left((a-b)+\sqrt{(a-b)^2-c^2}\right)^2+c^2\right\}^{\frac{1}{2}}}$$

$$\left.\begin{aligned}\sinh\theta &= \frac{a-b}{\left(c^2-(a-b)^2\right)^{\frac{1}{2}}}\\ \cosh\theta &= \frac{c}{\left(c^2-(a-b)^2\right)^{\frac{1}{2}}}\end{aligned}\right\} \text{No definition for QED}$$

$\cancel{P}$

$$\mathcal{L}_{\text{eff}} = -\mathcal{F} + \boxed{a\mathcal{F}^2 + b\mathcal{G}^2 + ic\mathcal{F}\mathcal{G}}$$