

Polarization observable for MCP in photon collisions:

theoretical considerations and experimental opportunities

Emidio Gabrielli

University and INFN, Trieste, Italy

NICPB, Tallinn, Estonia

in collaboration with: **L. Marzola, E. Milotti, M. Raidal, H. Veermäe**

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Theoretical motivations

- MCP's are fundamental particles (spin 0,½,1) with small EM charge

$$q = \epsilon e; \quad \epsilon \ll 1$$

- predicted by many “beyond Standard Model” scenarios
- natural framework: two or more U(1) coupled to different matter sectors
- implying existence of Dark Photons
- U(1) fields must have kinetic mixing $\chi \ll 1 \rightarrow$ tree-level or radiatively induced

$$\chi F_1^{\mu\nu} F_{2\mu\nu}$$

- matter fields in one U(1) sector appear as MCP in the other U(1) sector

Hidden sector becomes EM millicharged

$U(1)_1 \times U(1)_2 \rightarrow$ effective theory at low energy can mix the two $U(1)$
due to non-diagonal Wilson-Fisher renormalization

$\hat{A}_1^\mu$ photon $\rightarrow$ couple to both f_1 (ordinary matter) and f_2 (hidden sector)

ratio of charges

$$\epsilon = -\hat{e}_2 \chi / \hat{e}_1 \quad \text{millicharged}$$

$\hat{A}_2^\mu$ massless dark photon $\rightarrow$

- tree-level couplings only to hidden sector f_2
- to ordinary matter only via higher dim. operators
- not true for massive dark-photons
(it is impossible to diagonalize simultaneously mass and kinetic terms)

Fundamental Spin 1 MCP

E.Gabrielli, L.Marzola, M. Raidal, H.Veermae JHEP 1508 (2015) 150

- New features (different from $S = \frac{1}{2}, 0$), only recently analyzed
- asymptotic cross sections $\sigma(\gamma\gamma \rightarrow SS) \rightarrow 1/s$ for $E_{\text{CM}} = s^{1/2} \gg M_V$
- asymptotic energy behaviour $\sigma(VV) \rightarrow \varepsilon^4/M_V^2$, increases for small M_V
- identical property found in W^+ of EM interactions, $\sigma(WW) \rightarrow 1/v^2 \sim 80\text{pb}$

M. Katuya, PLB 124 (1983) 421

A. Denner, S. Dittmaier, R. Shuster, NPB 452 (1995) 80

- this is due to a **collinear enhancement** in $\gamma\gamma \rightarrow VV$ peculiar of fundamental charged spin-1 particles !
- **Unitarity satisfied**, but **Renormalizability** requires embedding of V into a multiplet of non-abelian gauge group which is spontaneously broken

EM interactions of Vectorial MCP

- Spin-1 MCP couplings to EM field are completely fixed by unitarity and gauge invariance
- Described by a complex field V_μ with mass m_V and charge Q_V

$$\mathcal{L}_{EM+V} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{1}{2}V_{\mu\nu}V^{\dagger\mu\nu} + m_V^2|V|^2 - iQ_V(g-1)F^{\mu\nu}V_\mu V_\nu^\dagger$$

model independent
Lagrangian

- unitarity requires gyromagnetic factor $g_V = 2$ (same as in SM for W)
S.Ferrara, M.Porrati, V.L. Telegdi, PRD 46 ('92)
- renormalizability requires the Higgs mechanism to generate V mass
- V as a component of non-abelian $SU(2)_D$ multiplet in the Dark sector

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SM EW group extended to

$$SU(2)_L \times SU(2)_D \times U(1)_Y$$

- a new Higgs Φ_D is required to break $SU(2)_D$ and to have milli-hypercharge ϵY
- new light neutral gauge-particle predicted

- No dedicated experiments targeting the MCP pair production through **photon-photon** scatterings exist so far
- experiments based on interferometric techniques with polarized photon beams can reveal direct MCP production
- Cross section enhancement of **spin-1 MCP** production expected in photon-photon scatterings with respect to $S=0, \frac{1}{2}$
- We computed polarized cross sections for MCP of **$S= \frac{1}{2}, 0, 1$**

$$\gamma(p_1, h_1) \gamma(p_1, h_1) \rightarrow \mu_S(p_3) \bar{\mu}_S(p_4)$$

E.Gabrielli, L.Marzola, E. Milotti, H.Vermaee ,

Polarization observables for MCP in photon collisions, **PRD 94 (2016) 095014**

Asymptotic energy behavior of cross sections

MCP $S=0$ $\sigma_{s \rightarrow \infty} / \sigma_0 = \frac{m_\epsilon^2}{4s}$

MCP $S=1/2$ $\sigma_{s \rightarrow \infty} / \sigma_0 = \frac{m_\epsilon^2}{2s} \log \left(\frac{s}{m_\epsilon^2} \right)$

MCP $S=1$ $\lim_{s/m_\epsilon \rightarrow \infty} \sigma_{S=1} = \frac{8\pi\alpha^2\epsilon^4}{m_\epsilon^2} \equiv \sigma_0$

this is due to the presence of double t-pole $\frac{d\sigma}{dt} \sim \frac{1}{(t - m_\epsilon^2)^2}$

$$\sigma_{S=1} > \sigma_{S=1/2} > \sigma_{S=0}$$

for same mass and coupling

Polarized total cross sections

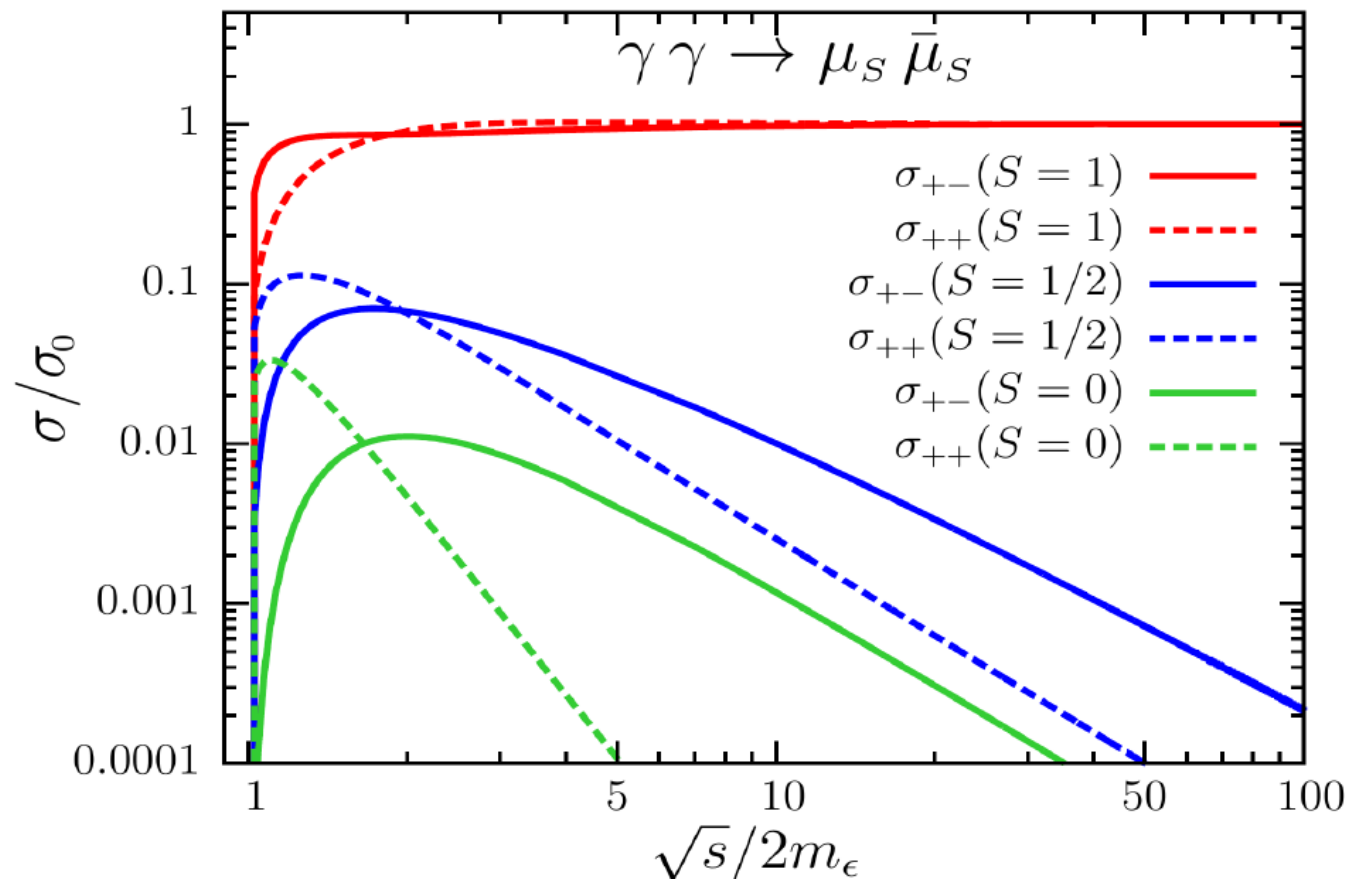
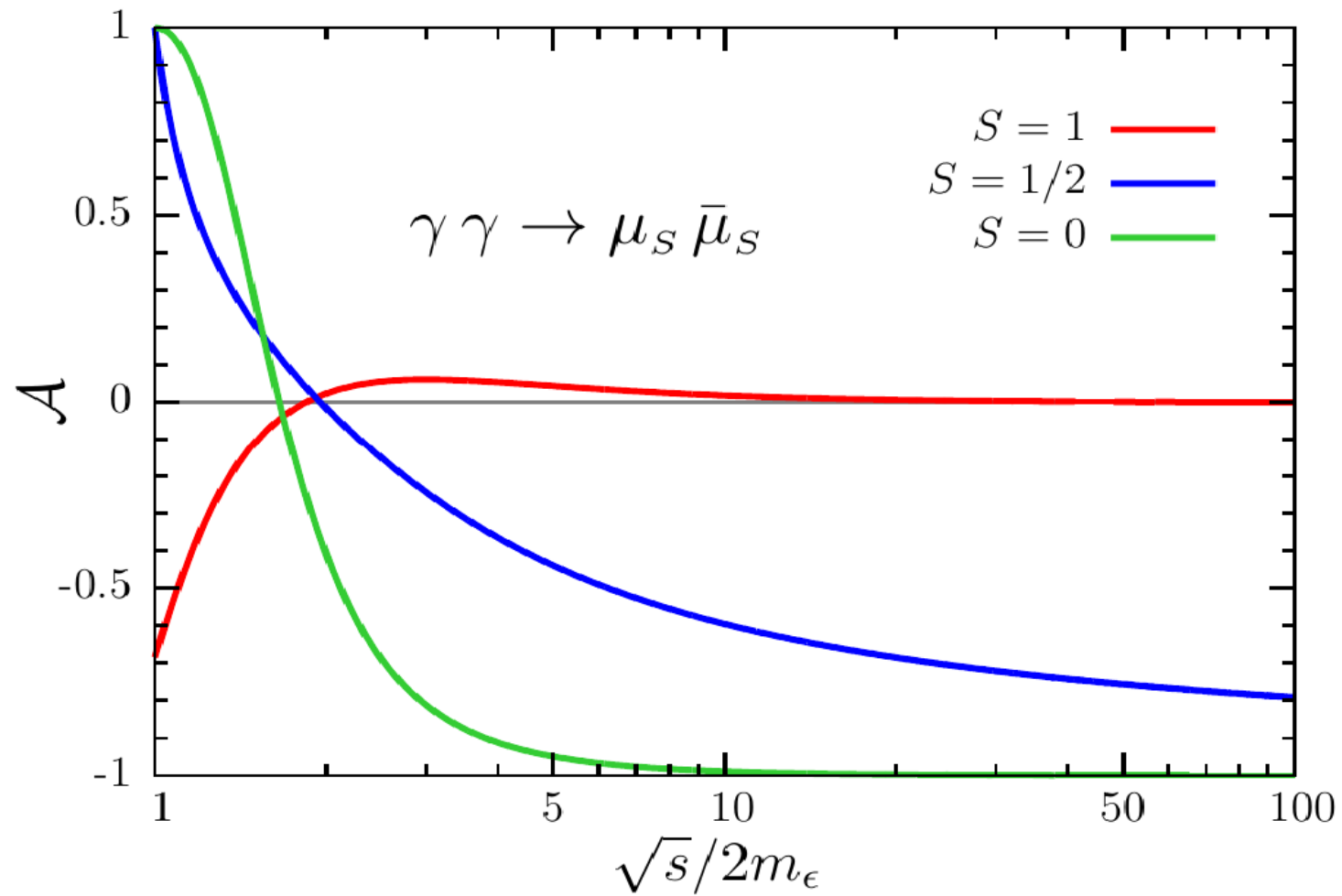


FIG. 2: Polarized cross sections for $S = 0$ (green), $S = 1/2$ (blue), $S = 1$ (red). A solid line denotes $\sigma_{+-} = \sigma_{-+}$ while the dashed line is $\sigma_{++} = \sigma_{--}$.

$\sigma(S=1)$ largely dominates ($\rightarrow$ constant) $\sigma(S=1/2)$ and $\sigma(S=0)$ above 2 times the threshold-energy production of MPC pairs

Polarization Asymmetry

$$\mathcal{A} = \frac{\sigma_{++} + \sigma_{--} - \sigma_{+-} - \sigma_{-+}}{\sigma}$$

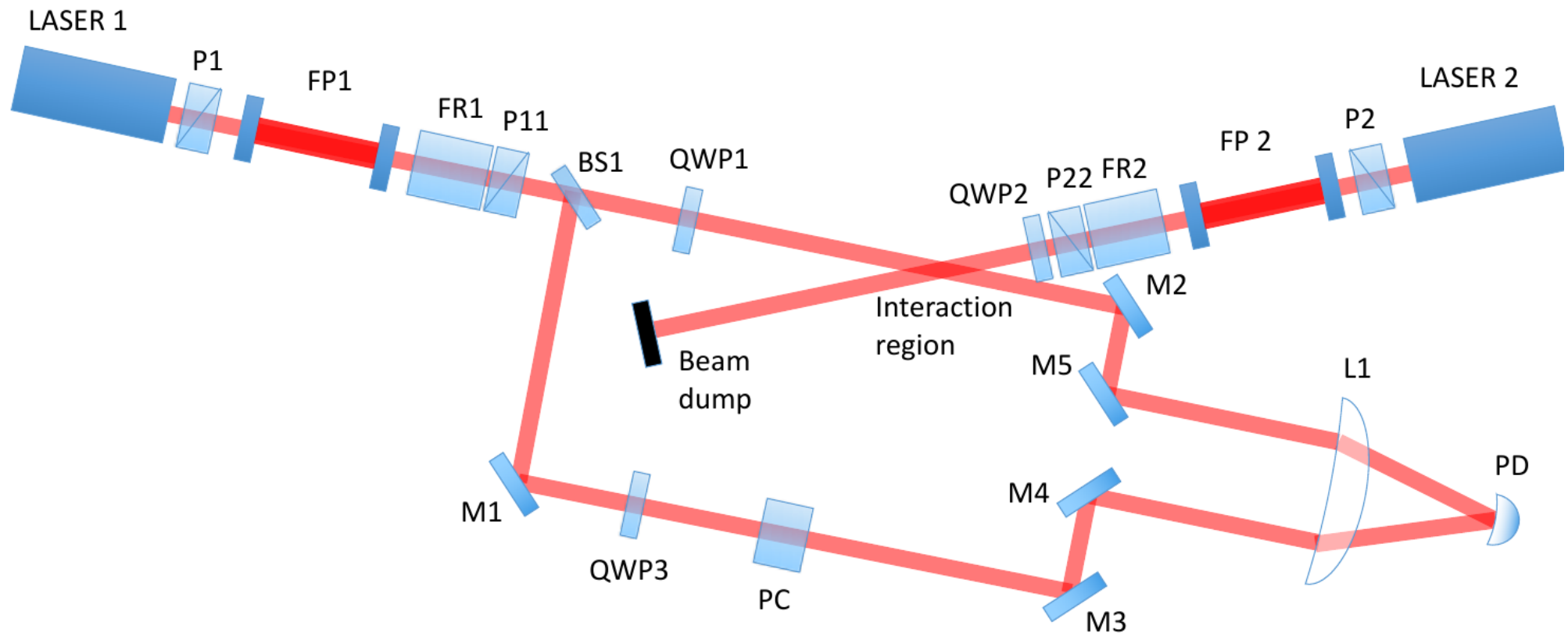


Interferometric detection of photon-photon scattering and its experimental sensitivity to MCPs

$S=0,1$ very sensitive to polarizations

$S=1$ almost insensitive to polarizations for $\sqrt{s}/2m_\epsilon \gtrsim 5$

We need a sensitive detection scheme where we have complete control of photon polarization



Two independent laser beams – main beam LASER 1 and probe beam LASER 2

- FP1 and FP2 are Fabry-Perot cavities
- FR1 and FR2 are Faraday cells
- PC is a Pockels cell
- P1 and P2, P11 and P22 are polarizers
- QWP1-QWP3 are quarter-wave plates
- BS1 beam splitter
- the optical elements used for balancing are omitted
- M1-M5 are mirrors
- the beams are combined by the convex lens L1
- the optical path lengths are tuned to have a dark fringe on the photodiode PD

When the laser power is $P_{1,2}$, with corresponding intensities $I_{1,2}$ in the interaction region, the density of photons from the first beam in the interaction region is

$$I_1/h\nu c$$

so that – if the volume of the interaction region is V_{12} – the total interaction area is

$$\sigma V_{12} I_1 / h\nu c$$

and this in turn means that the total number of scatterings per unit time is

$$\frac{\sigma}{(h\nu)^2 c} V_{12} I_1 I_2$$

Finally, the irradiance of the main beam becomes

$$I'_1 = I_1 - \frac{\sigma \lambda}{hc^2} f_1 I_1 I_2$$


geometric factor

$$\delta I = \frac{\sigma \lambda}{hc^2} f_1 I_1 I_2$$

main-beam irradiance change

To recover the small intensity change due to beam-beam interactions we have to fight off noise, and to this end we modulate at least one of the beams.

We must modulate also to linearize the dependence on the tiny cross-section

$$I_1'(t) = I_1(t) - \frac{\sigma \lambda}{hc^2} f_1 I_1(t) I_2(t)$$

i.e., in general we must take

$$I_{1,2}(t) = I_{1,2}^{(0)} [1 + m_{1,2} \cos(\omega_{1,2}t + \varphi_{1,2})]$$

Next, we must analyze the interference detection scheme.

Beam interference

(here we assume that the beams have the same wavelength)

$$\mathbf{E}_{\text{tot}}(\mathbf{x}, t) = \mathbf{E}_A(\mathbf{x}) \cos(\omega t) + \mathbf{E}_B(\mathbf{x}) \cos(\omega t + \varphi)$$

then the total irradiance is

$$I_{\text{tot}} = \epsilon_0 c \langle |\mathbf{E}_{\text{tot}}|^2 \rangle = I_A + I_B + 2\sqrt{I_A I_B} \cos \varphi$$

When we operate the apparatus at the dark fringe we take $\varphi = \pi$, and the irradiance is at a minimum

$$I_{\text{tot}} = I_A + I_B - 2\sqrt{I_A I_B}$$

In this dark fringe condition, and with balanced beams, we find

$$I_A = I_B = I_1^{(0)}; \quad I_{\text{tot}} = I_A + I_B - 2\sqrt{I_A I_B} = 0$$

and when they are off-balance and static

$$I_A = I_1^{(0)}; \quad I_B = I_1^{(0)} - \delta I; \quad I_{\text{tot}} \approx \frac{\delta I^2}{4I_1^{(0)}}$$

$$\delta I = \frac{\sigma \lambda}{hc^2} f_1 I_1 I_2$$

The **dependence on the square of the unbalance is annoying** – we need a linear dependence to achieve a reasonable sensitivity in the evaluation of the cross-section – but **this can be corrected by phase-modulating one of the beams**

Signal

When we let

$$I_0 = I_1^{(0)}$$

$$I_{\text{probe}} = I_2$$

$$m_{\text{probe}} = m_2$$

$$R_{\text{det}} = \text{beam spot size}$$

$$\delta P = \pi R_{\text{det}}^2 \delta I = \text{detected power}$$

$$q = \text{quantum efficiency}$$

$$i = qP$$

we find

$$\delta I = \frac{\sigma \lambda}{hc^2} f_1 I_0 I_{\text{probe}} m_{\text{probe}}$$

$$\delta P = \pi R_{\text{det}}^2 \delta$$

$$i_S = q\pi R_{\text{det}}^2 \delta$$

$$\langle i_S^2 \rangle = \frac{1}{2} (q\pi R_{\text{det}}^2 \delta I)^2$$

Here we assume a sinusoidal time dependence

} Amplitudes

Noise

Noise current has several sources

$$i_{\text{RMS}}^2 = i_{\text{shot}}^2 + i_{\text{dark}}^2 + i_{\text{therm}}^2 + i_{\text{rin}}^2$$

shot noise

$$i_{\text{shot}}^2 = 2e\sqrt{\langle i_S^2 \rangle} \Delta\nu = \sqrt{2}e(q\pi R_{\text{det}}^2 \delta I) \Delta\nu$$

dark current

$$i_{\text{dark}}^2 = \frac{V_{\text{dark}}^2 \Delta\nu}{G^2}$$

thermal noise

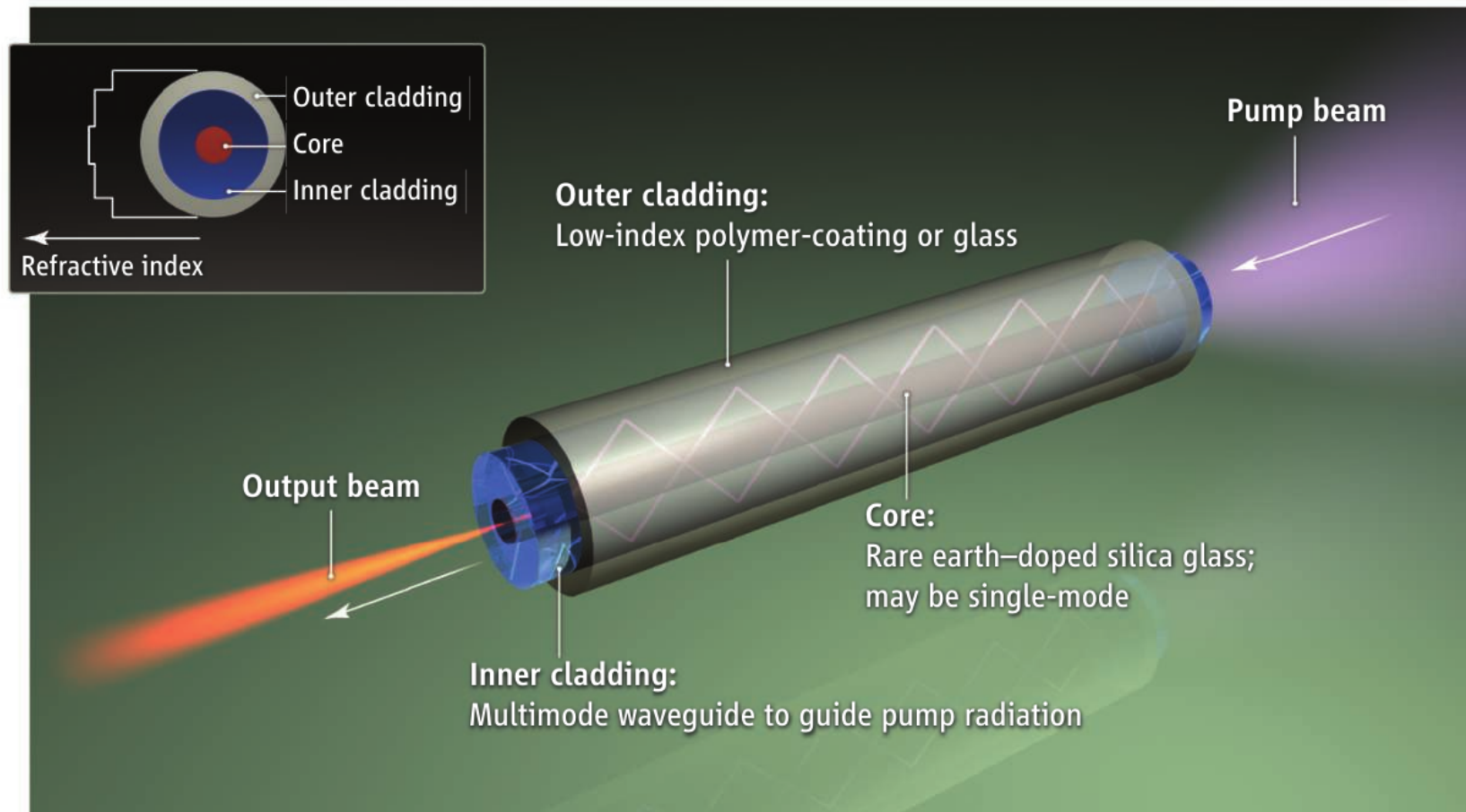
$$i_{\text{therm}}^2 = \frac{4k_B T \Delta\nu}{G}$$

relative intensity noise

$$i_{\text{rin}}^2 = q^2 (\pi R_{\text{det}}^2 I_0) \text{RIN}(\omega_0) \Delta\nu$$

Laser source

The effect is minute, and **one candidate source is a fiber laser**. Fiber lasers deliver increasingly high power, with good beam features



Fiber lasing. Schematic of a double-clad fiber laser in an end-pumped configuration (not to scale).

Example of commercial CW high-power fiber lasers from IPG Photonics

- ▶ Single-mode up to 20 kW
- ▶ Multi-mode up to 500 kW
- ▶ Excellent BPP
- ▶ Constant BPP Over Entire Power Range
- ▶ Small Focus over Large Working Distance
- ▶ Record Wall-plug Efficiency up to 50%
- ▶ Dynamic Range from 10 to 100%
- ▶ Optional Affixed Chiller
- ▶ Maintenance-free Operation
- ▶ Modular 'Plug & Play' Design
- ▶ Compact, Rugged & Easy to Install
- ▶ Integrated Coupler, Beam Sharer or Switch Options

YLS, 1-100 kW

Ytterbium CW Laser Systems

YLS low-order-mode Ytterbium fiber laser systems range from 1 to 100 kW, operating in CW or modulated modes up to 5 kHz with wall-plug efficiencies over 40%. They have dynamic range from 10% to full power with no change in beam divergence or beam profile, allowing a single laser to be utilized for both high and low-power applications such as welding, drilling and precision cutting, a previously unheard of capability. The high brightness allows the use of long focal length processing lenses for vastly improved depth of field and minimal damage to optical components. The units can be supplied with fiber lengths up to 100 meters, different fiber diameters and variety of multi-port beam switches, beam couplers, termination optics and scanners.



Numerical estimates

- laser power ≈ 50 kW (example, fiber laser IPG Photonics, YLS series)

- $\lambda = 1075$ nm

- $m_{probe} = 1$

- $R = 1$ mm

- $f_1 = 0.1$ m

- $T = 300$ K

- $q = 0.7$ A/W

- $G = 10^7$ V/A

- $V_{dark} = 2 \mu\text{V}/\text{Hz}^{1/2}$

- $\text{RIN} \approx 10^{-14} \text{ Hz}^{-1/2}$

- $\Delta\nu \approx 1 \mu\text{Hz}$

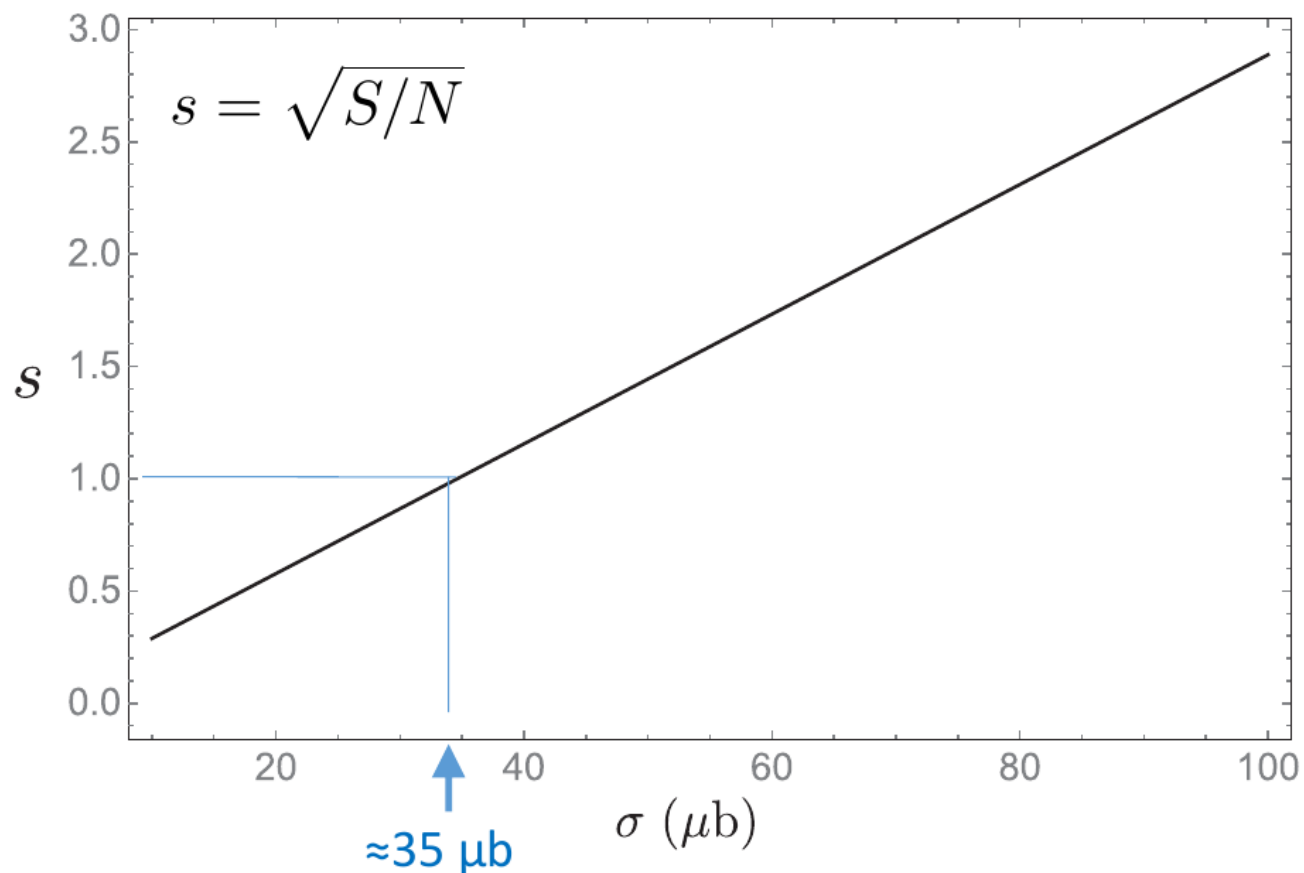


FIG. 7. Sensitivity $s = \sqrt{S/N}$ as a function of the cross section

Conclusions

- $S=1$ MCPs are interesting objects with unusual properties (similar to SM W 's).
- $S=1$ MCPs defy recent limits on other types of millicharged particles, and could be interesting DM candidates.
- The experimental layout is a true low-energy photon-photon collider, polarization-dependent and with a sensitive detection scheme.
- The apparatus is conceived for MCP search, but could easily be used for other searches; there is additional flexibility in the choice of laser wavelengths and shape of interaction region.

Backup slides

When we phase-modulate one beam in the interferometric detector, we find

$$I_{\text{tot}} = \left(2I_1^{(0)} - \delta I\right) (1 + \cos \varphi(t)) \approx \frac{\alpha(t)^2}{2} \left(2I_1^{(0)} - \delta I\right)$$

where

$$\varphi(t) = \pi + \alpha(t); \quad |\alpha(t)| \ll 1$$

The smallness of alpha is instrumental to the series expansion; we can take larger values of alpha, but the Fourier expansion that follows involves less-intuitive Bessel functions.

With the proper modulation we can retrieve the amplitude of the term which contains the physical information

$$\frac{\alpha(t)^2}{2} \delta I$$

When we take

$$\alpha(t) = \alpha_0 \cos(\omega_{PC}t + \varphi_{PC})$$

and we modulate the probe beam so that

$$I_1(t) = I_1^{(0)}$$

$$I_2(t) = I_2^{(0)} [1 + m_2 \cos(\omega_2 t + \varphi_2)]$$

we see that the total irradiance is

$$I'_1(t) = \left(I_1^{(0)} - \frac{\sigma \lambda}{hc^2} f_1 I_1^{(0)} I_2^{(0)} \right) - \frac{\sigma \lambda}{hc^2} f_1 I_1^{(0)} I_2^{(0)} m_2 \cos(\omega_2 t + \varphi_2)$$

and therefore we can recover the amplitude $\frac{\sigma \lambda}{hc^2} f_1 I_1^{(0)} I_2^{(0)} m_2$ from the spectral components at frequency $2\omega_{PC} \pm \omega_2$.

From the previous expansion, their amplitude is

$$\frac{\alpha_0^2}{2} \frac{\sigma \lambda}{hc^2} f_1 I_1^{(0)} I_2^{(0)} m_2$$