Аномальные константы для вершины γγγZ в фотон-фотонном рассеянии на коллайдере CLIC

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План доклада

- Линейный коллайдер CLIC. Реальные фотоны, сгенерированные путем обратного комптоновского рассеяния лазерных фотонов на поляризованных пучках электронов.
- Эффективный Лагранжиан и аномальные калибровочные константы для вершины $\gamma\gamma\gamma Z$.
- Дифференциальные и полные сечения для процесса $\gamma\gamma \to \gamma Z$ с поляризованными начальными фотонами.
- Области значений аномальных констант, которые могут быть исключены на CLIC.
- Сравнение с результатами, полученными для других коллайдеров.

γZ production in light-by-light (LBL) scattering

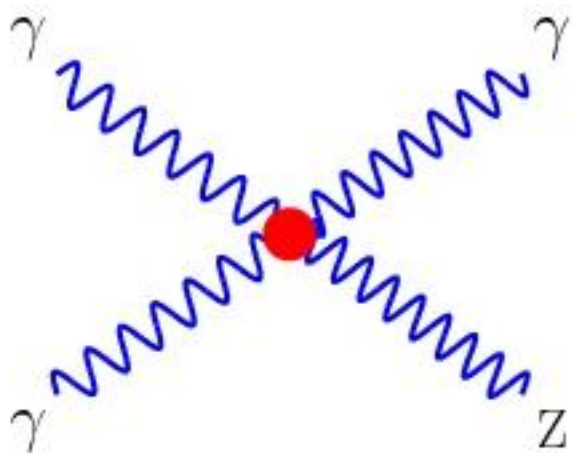
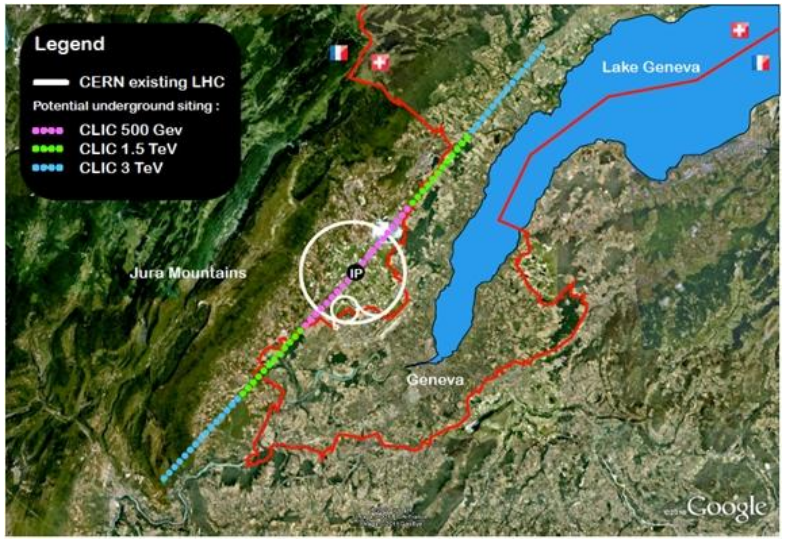


Diagram for process γγ → γZ

The goal is to examine anomalous quartic gauge couplings (QGCs) via reaction γγ → γZ at the CLIC

Compact LInear Collider (CLIC)



	Beam energy	Integrated luminosity (unpolarized beams)
1st stage	190 GeV	1000 fb^{-1}
2nd stage	750 GeV	2500 fb^{-1}
3rd stage	1500 GeV	5000 fb^{-1}

λ_0 is helicity of laser *photon beam*, and λ_e is helicity of *electron beam* before Compton backscattering (CB)

$$(\lambda_e^{(1)}, \lambda_0^{(1)}; \lambda_e^{(2)}, \lambda_0^{(2)}) = (0.8, 1; 0.8, 1)\ ,$$
$$(\lambda_e^{(1)}, \lambda_0^{(1)}; \lambda_e^{(2)}, \lambda_0^{(2)}) = (-0.8, 1; -0.8, 1)$$

CLIC energy stages and integrated luminosities for unpolarized and polarized electron beams

		L, fb^{-1}		
Stage	$\sqrt{s}$, GeV	$\lambda_e = 0$	$\lambda_e = -0.8$	$\lambda_e = 0.8$
2	1500	2500	2000	500
3	3000	5000	4000	1000

Differential cross section

$$\frac{d\sigma}{d\cos\theta} = \frac{\beta}{128\pi s} \int\limits_{x_{1\,\min}}^{x_{\max}} \frac{dx_1}{x_1} f_{\gamma/e}(x_1) \int\limits_{x_{2\,\min}}^{x_{\max}} \frac{dx_2}{x_2} f_{\gamma/e}(x_2)$$

$$\times \Bigg\{ \left[1+\xi\left(E_\gamma^{(1)},\lambda_0^{(1)}\right)\right]\left[1+\xi\left(E_\gamma^{(2)},\lambda_0^{(2)}\right)\right] \sum_{\lambda_3\lambda_4} |M_{++\lambda_3\lambda_4}|^2$$

$$+ \left[1+\xi\left(E_\gamma^{(1)},\lambda_0^{(1)}\right)\right]\left[1-\xi\left(E_\gamma^{(2)},\lambda_0^{(2)}\right)\right] \sum_{\lambda_3\lambda_4} |M_{+-\lambda_3\lambda_4}|^2$$

$$+ \left[1-\xi\left(E_\gamma^{(1)},\lambda_0^{(1)}\right)\right]\left[1+\xi\left(E_\gamma^{(2)},\lambda_0^{(2)}\right)\right] \sum_{\lambda_3\lambda_4} |M_{-+\lambda_3\lambda_4}|^2$$

$$+ \left[1-\xi\left(E_\gamma^{(1)},\lambda_0^{(1)}\right)\right]\left[1-\xi\left(E_\gamma^{(2)},\lambda_0^{(2)}\right)\right] \sum_{\lambda_3\lambda_4} |M_{--\lambda_3\lambda_4}|^2 \Bigg\}$$

$f_{\gamma/e}(x)$ - distribution of CB photon in energy fraction $x = E_\gamma/E_e$

$\xi(E_\gamma,\lambda_0)$ - photon helicity

$\beta = 1 - m_Z^2/s$

$$\xi(E_\gamma, \lambda_0) = \frac{\lambda_0(1-2r)[1-x+1/(1-x)] + \lambda_e r\zeta[1+(1-x)(1-2r)^2]}{1-x+1/(1-x)-4r(1-r)-\lambda_e\lambda_0 r\zeta(2r-1)(2-x)} ,$$

where $x = E_\gamma/E_e$, $r = x/\zeta(1-x)$, $\zeta = 4E_eE_0/m_e^2$, m_e being the electron mass.

$$f_{\gamma/e}(x) = \frac{1}{g(\zeta)}\Big[1 - x + \frac{1}{1-x} - \frac{4x}{\zeta(1-x)} + \frac{4x^2}{\zeta^2(1-x)^2} + \lambda_0\lambda_e r\zeta(1-2r)(2-x)\Big],$$

where

$$g(\zeta) = g_1(\zeta) + \lambda_0\lambda_e\, g_2(\zeta) ,$$

$$g_1(\zeta) = \left(1 - \frac{4}{\zeta} - \frac{8}{\zeta^2}\right)\ln(\zeta+1) + \frac{1}{2} + \frac{8}{\zeta} - \frac{1}{2(\zeta+1)^2} ,$$

$$g_2(\zeta) = \left(1 + \frac{2}{\zeta}\right)\ln(\zeta+1) - \frac{5}{2} + \frac{1}{\zeta+1} - \frac{1}{2(\zeta+1)^2} .$$

Effective Lagrangian

Effective Lagrangian of dimension-8 operators which contribute to anomalous *quartic neutral gauge couplings*

$$\mathcal{L}_{\rm QNGC} = \frac{c_8}{\Lambda^4} B_{\rho\sigma} B^{\rho\sigma} B_{\mu\nu} B^{\mu\nu} + \frac{c_9}{\Lambda^4} W^a_{\rho\sigma} W^{a\rho\sigma} W^b_{\mu\nu} W^{b\mu\nu} + \frac{c_{10}}{\Lambda^4} W^a_{\rho\sigma} W^{b\rho\sigma} W^a_{\mu\nu} W^{b\mu\nu}$$
$$+ \frac{c_{11}}{\Lambda^4} B_{\rho\sigma} B^{\rho\sigma} W^a_{\mu\nu} W^{a\mu\nu} + \frac{c_{13}}{\Lambda^4} B_{\rho\sigma} B^{\sigma\nu} B_{\nu\mu} B^{\mu\rho} + \frac{c_{14}}{\Lambda^4} W^a_{\rho\sigma} W^{a\sigma\nu} W^b_{\nu\mu} W^{b\mu\rho}$$
$$+ \frac{c_{15}}{\Lambda^4} W^a_{\rho\sigma} W^{b\sigma\nu} W^a_{\nu\mu} W^{b\mu\rho} + \frac{c_{16}}{\Lambda^4} B_{\rho\sigma} B^{\sigma\nu} W^a_{\nu\mu} W^{a\mu\rho}$$

→ **Effective Lagrangian for anomalous γγγZ couplings**

$$L_{\gamma\gamma\gamma Z} = g_1 (F^{\rho\mu} F^{\alpha\nu})(\partial_\rho F_{\mu\nu} Z_\alpha) + g_2 (F^{\rho\mu} F^{\nu}_{\mu})(\partial_\rho F_{\alpha\nu} Z^\alpha)$$

Anomalous couplings g_1, g_2 have dimension -4

Another effective Lagrangian for anomalous γγγZ couplings

$$L_{\gamma\gamma\gamma Z} = \varsigma_1 (F_{\mu\nu} F^{\mu\nu})(F_{\rho\sigma} Z^{\rho\sigma}) + \varsigma_2 (F_{\mu\nu} \tilde{F}^{\mu\nu} F_{\rho\sigma} \tilde{Z}^{\rho\sigma})$$

(Baldenegro et al., JHEP 06, 142 (2017))

→ **Relations between two sets of coupling constants**

$$g_1 = 8(\varsigma_2 - \varsigma_1), \quad g_2 = 8\varsigma_2$$

Feynman rule for the vertex γγγZ

$$
\begin{aligned}
P^{\mu\nu\rho\alpha} = \mathcal{P}\{ & g_1[(p_1\cdot p_2)(p_2\cdot p_3)g^{\mu\nu}g^{\rho\alpha} - (p_1\cdot p_3)p_2^{\mu}p_1^{\nu}g^{\rho\alpha} \\
& - (p_1\cdot p_3)p_1^{\nu}p_2^{\alpha}g^{\mu\rho} + p_2^{\mu}p_1^{\nu}p_1^{\rho}p_3^{\alpha}] \\
& + g_2[-(p_1\cdot p_2)(p_1\cdot p_3)g^{\mu\alpha}g^{\nu\rho} + (p_2\cdot p_3)p_1^{\nu}p_1^{\alpha}g^{\mu\rho} \\
& - (p_2\cdot p_3)p_1^{\nu}p_1^{\rho}g^{\mu\alpha} + (p_2\cdot p_3)p_1^{\nu}p_2^{\alpha}g^{\mu\rho} + 2(p_2\cdot p_3)p_2^{\mu}p_1^{\rho}g^{\nu\alpha} \\
& - (p_1\cdot p_3)p_2^{\rho}p_1^{\alpha}g^{\mu\nu} + p_3^{\mu}p_1^{\nu}p_2^{\rho}p_1^{\alpha}]\}
\end{aligned}
$$

$\mathcal{P}$ – permutations *(symmetrization with respect to photon's momenta and indices)*

$$
M_{\lambda_1\lambda_2\lambda_3\lambda_4}(p_1,p_2,p_3) = P_{\mu\nu\rho\alpha}(p_1,p_2,p_3)\,\varepsilon_{\mu}^{\lambda_1}(p_1)\varepsilon_{\nu}^{\lambda_2}(p_2)\varepsilon_{\rho}^{*\lambda_3}(p_3)\varepsilon_{\alpha}^{*\lambda_4}(p_4)
$$

→ **24 helicity amplitudes proportional to g_1**
24 helicity amplitudes proportional to g_2

Differential and total cross sections

Electron beam helicities:

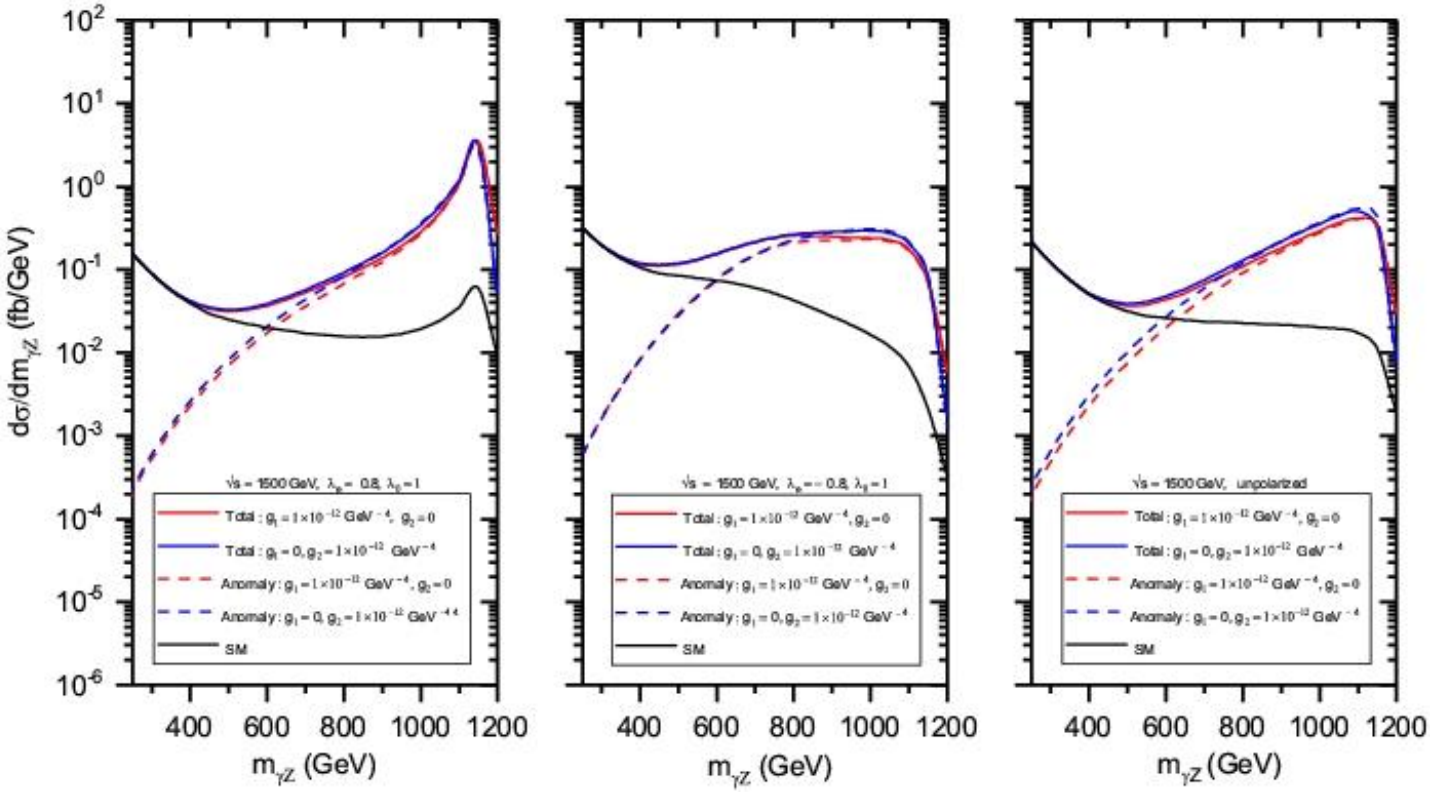
λ_e = 0.8, -0.8, and 0 (unpolarized case)

Cuts on the invariant mass and rapidities of final photons:

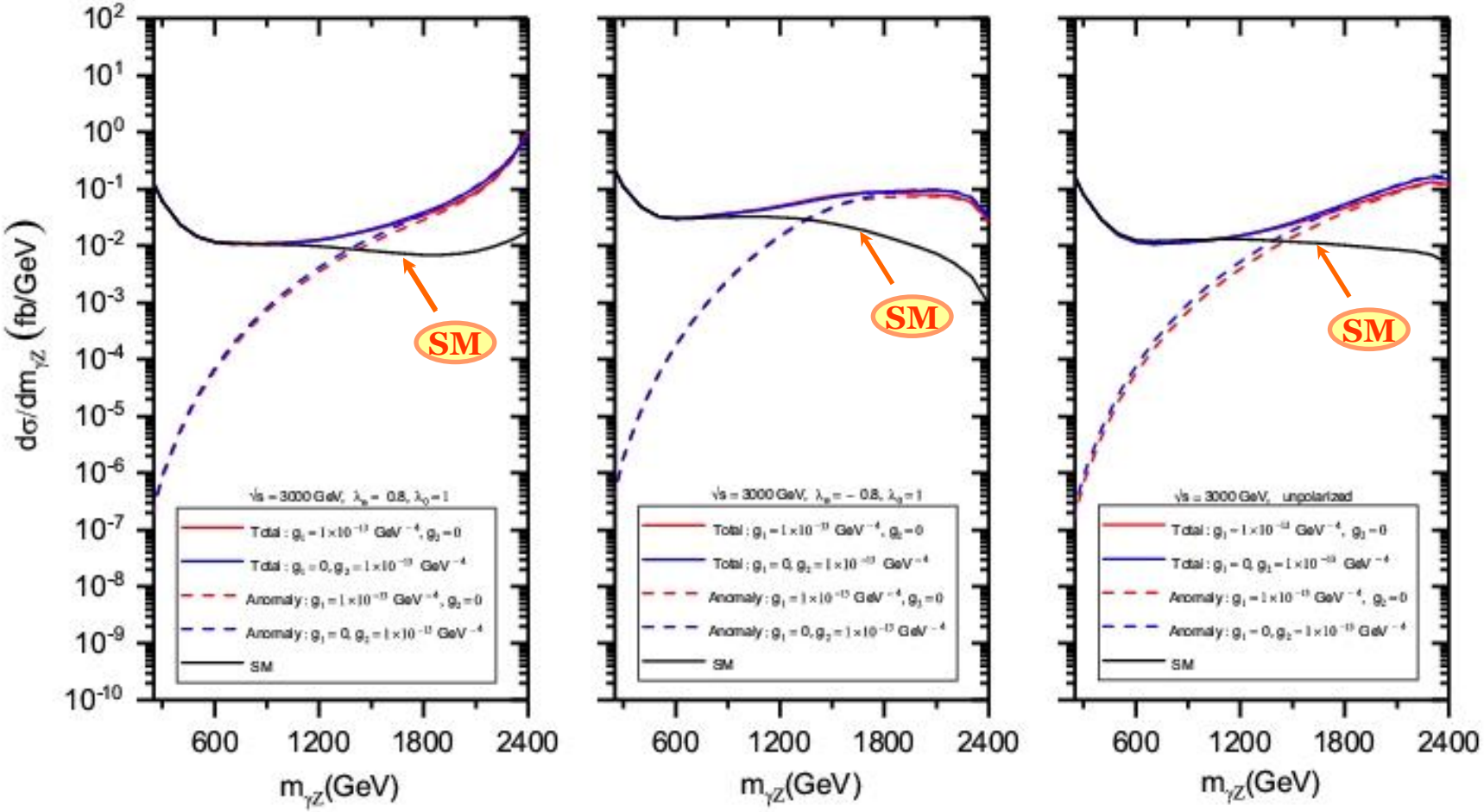
$m_{\gamma Z} > 200$ GeV, $|\eta| < 2.5$

SM amplitude:

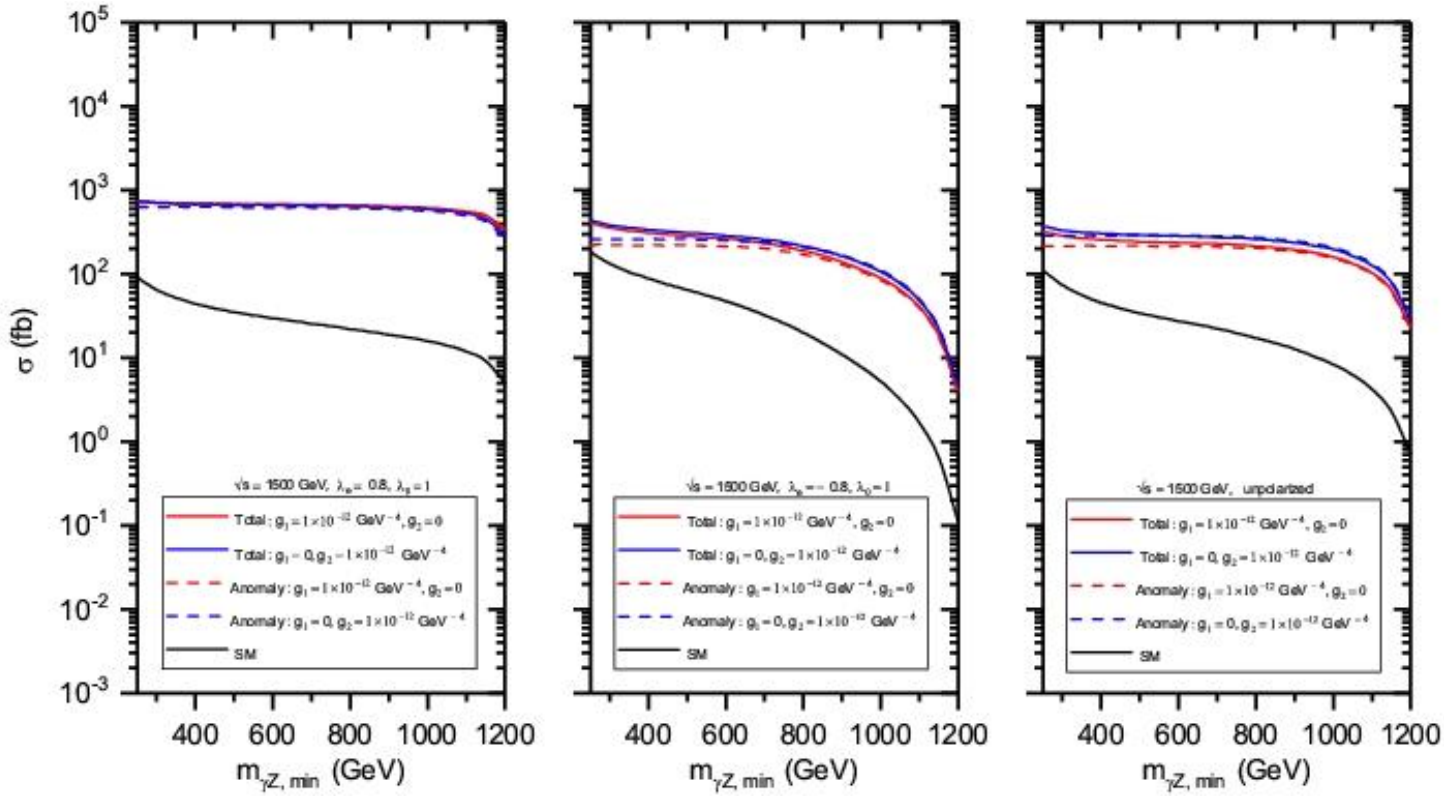
M_W (W-loop, dominates at $\sqrt{s} > 200$ GeV) + M_f (fermion-loop) contributions



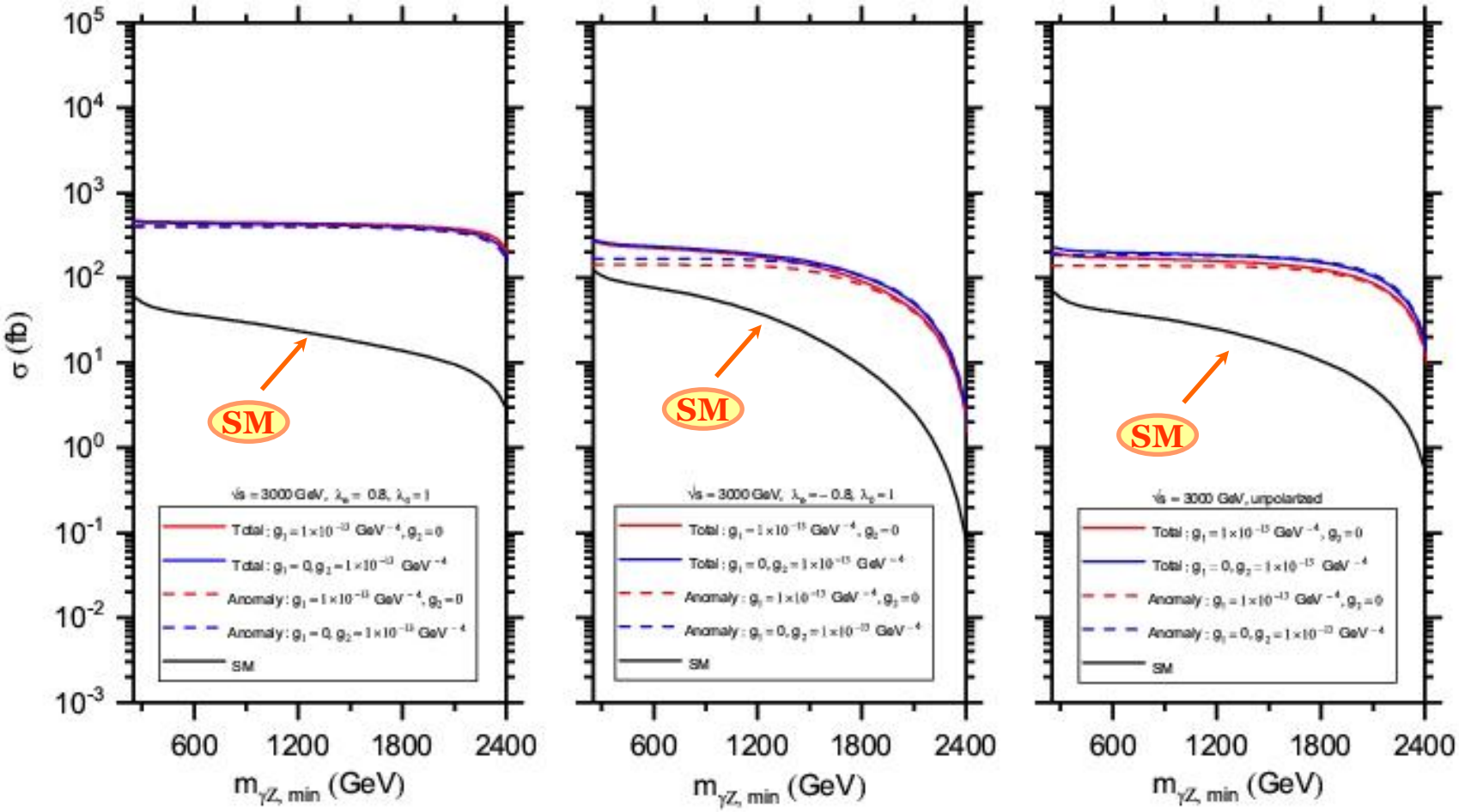
Differential cross sections for the process γγ → γZ as functions of invariant mass of outgoing photons at √s = 1.5 TeV. The left, middle and right panels correspond to λ_e= 0.8, -0.8, 0. The curves are (from top downwards): full, pure anomaly, SM cross sections.



The same as in the previous figure, but for collision energy 3.0 TeV.



Total cross sections for the process γγ → γZ as functions of minimal invariant mass of outgoing photons at √s = 1.5 TeV. The left, middle and right panels correspond to λ_e= 0.8, -0.8, 0. The curves are (from top downwards): full, pure anomaly, SM cross sections.



The same as in the previous figure, but for the collision energy 3.0 TeV.

Exclusion significance (δ = percentage systematic error)

$$S_{\mathrm{excl}} = \sqrt{2}\left[s - b\ln\left(\frac{b+s+x}{2b}\right) - \frac{1}{\delta^2}\ln\left(\frac{b-s+x}{2b}\right) - (b+s-x)\left(1+\frac{1}{\delta^2 b}\right)\right]^{1/2}$$

s (b) = number of signal (background) events

$$x = \sqrt{(s+b)^2 - 4\delta^2 s b^2/(1+\delta^2 b)}$$

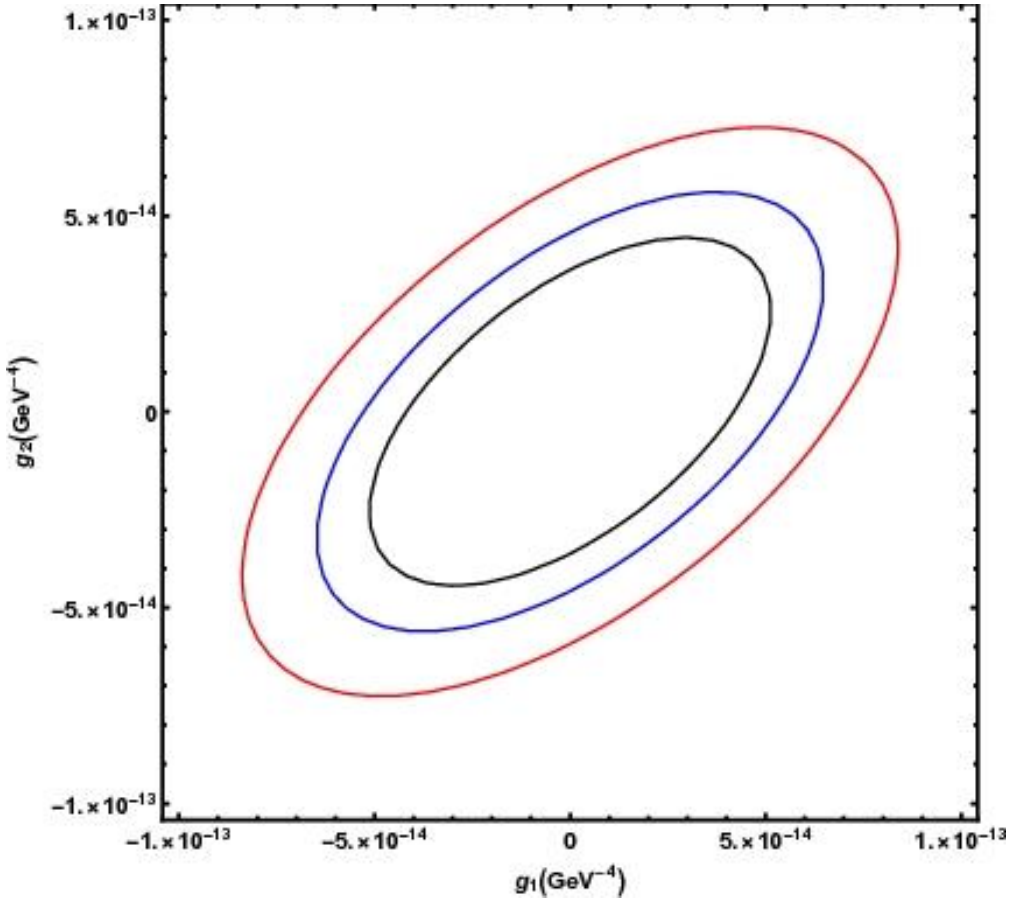
In the limit δ = 0:

$$S_{\mathrm{excl}} = \sqrt{2\left[s - b\ln\left(1+\frac{s}{b}\right)\right]}$$

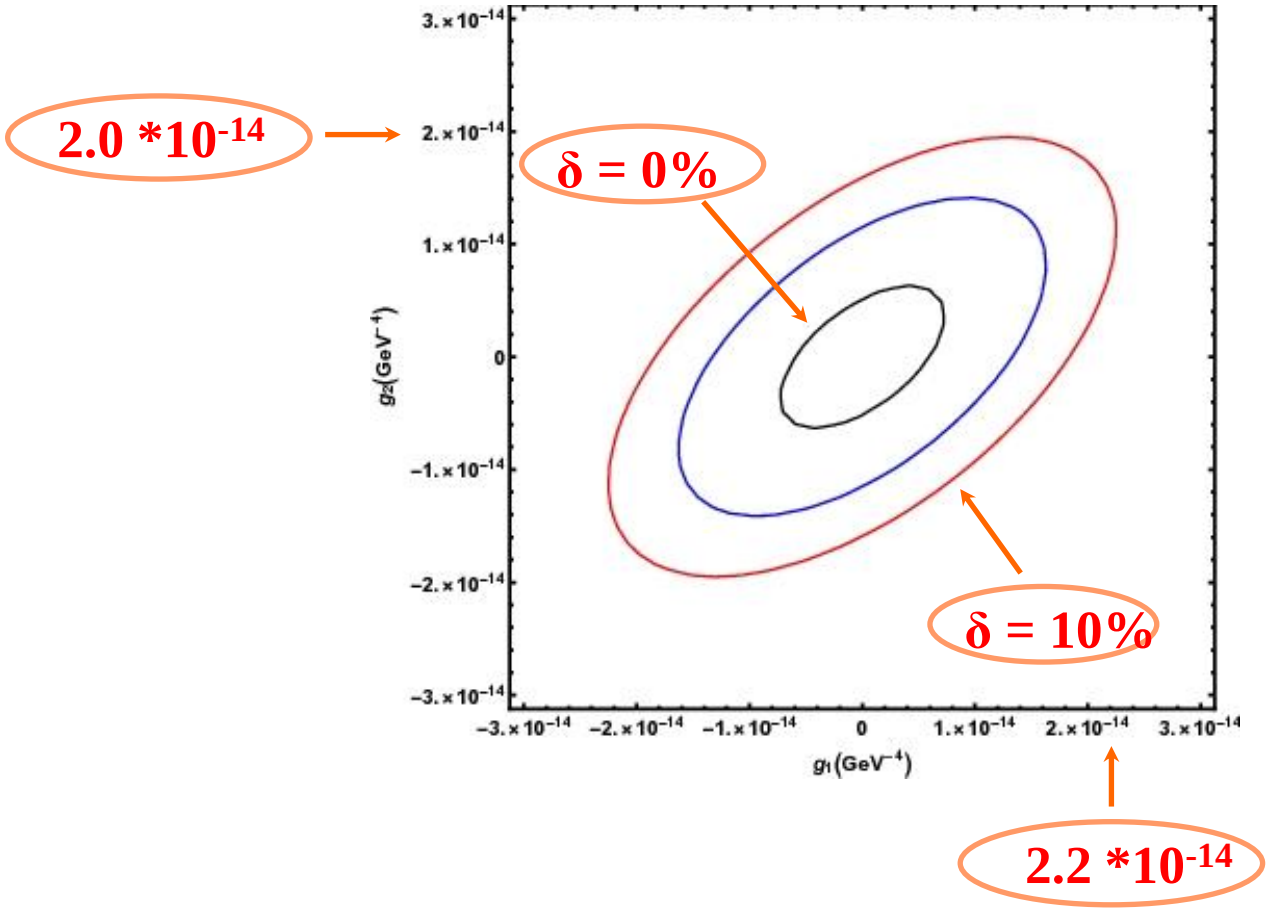
s << b →

$$S_{\mathrm{excl}} = \frac{s}{\sqrt{b}}$$

S_{excl} ≤ 1.645 is the region that can be excluded at 95% C.L.



95% C.L. exclusion region for anomalous couplings g_1, g_2 for *unpolarized* LBL scattering at the CLIC. Systematic errors are 0%, 5%, and 10%. The collision energy is 1.5 TeV, the integrated luminosity is 2.5 ab^{-1}.



The same as in the previous figure, but for the collision energy 3.0 TeV and integrated luminosity 5 ab^{-1}. Couplings g_1, g_2 are in GeV^{-4}.

Exclusion limits on anomalous couplings at the CLIC for energy 3.0 TeV, and cut $m_{\gamma Z}$ > 1000 GeV. *Polarized* case

λ_e		0	−0.8	0.8
L, fb^{-1}		5000	4000	1000
$\lvert g_1\rvert$, GeV^{-4} ($g_2 = 0$)	$\delta = 0\%$	5.98×10^{-15}	7.14×10^{-15}	5.13×10^{-15}
	$\delta = 5\%$	1.33×10^{-14}	1.73×10^{-14}	7.79×10^{-15}
	$\delta = 10\%$	1.85×10^{-14}	2.39×10^{-14}	1.04×10^{-14}
$\lvert g_2\rvert$, GeV^{-4} ($g_1 = 0$)	$\delta = 0\%$	5.18×10^{-15}	6.62×10^{-15}	5.19×10^{-15}
	$\delta = 5\%$	1.16×10^{-14}	1.60×10^{-14}	7.87×10^{-15}
	$\delta = 10\%$	1.62×10^{-14}	2.21×10^{-14}	1.05×10^{-14}

Bounds on anomalous couplings for the LHC and HL-LHC

SM expectation: $Br(Z \to \gamma\gamma\gamma) = 5.41*10^{-10}$

$Br(Z \to \gamma\gamma\gamma) < 0.8*10^{-5}$ (LEP)
$Br(Z \to \gamma\gamma\gamma) < 2.2*10^{-6}$ (ATLAS)

→ $|\zeta_i| < 1.3\ 1.0*10^{-9}\ GeV^{-4}$

From $\gamma\gamma \to \gamma Z$ at LHC:

LHC, $L=300\ fb^{-1}$:
$|\zeta_i| < 1.0*10^{-13}\ GeV^{-4}$

HL-LHC, $L=3\ ab^{-1}$:
$|\zeta_i| < 7.8*10^{-14}\ GeV^{-4}$

(Baldenegro et al., JHEP 06, 142 (2017))

Recall that $g_i \approx 8\zeta_i$

Заключение

- Изучены аномальные константы для **вершины** $\gamma\gamma\gamma Z$ в рассеянии реальных фотонов, полученных в обратном комптоновском рассеянии лазерных фотонов на поляризованных электронных пучках на CLIC.
- Вычислены дифференциальные и полные сечения для процесса $\gamma\gamma \to \gamma Z$.
- Получены области значений аномальных констант, которые могут быть исключены в фотон-фотонном рассеянии на CLIC.
- Показано, что ограничения CLIC на один-два порядка жестче, чем аналогичные ограничения, полученные для LHC и HL-LHC.

Спасибо за внимание!

Пора за работу!

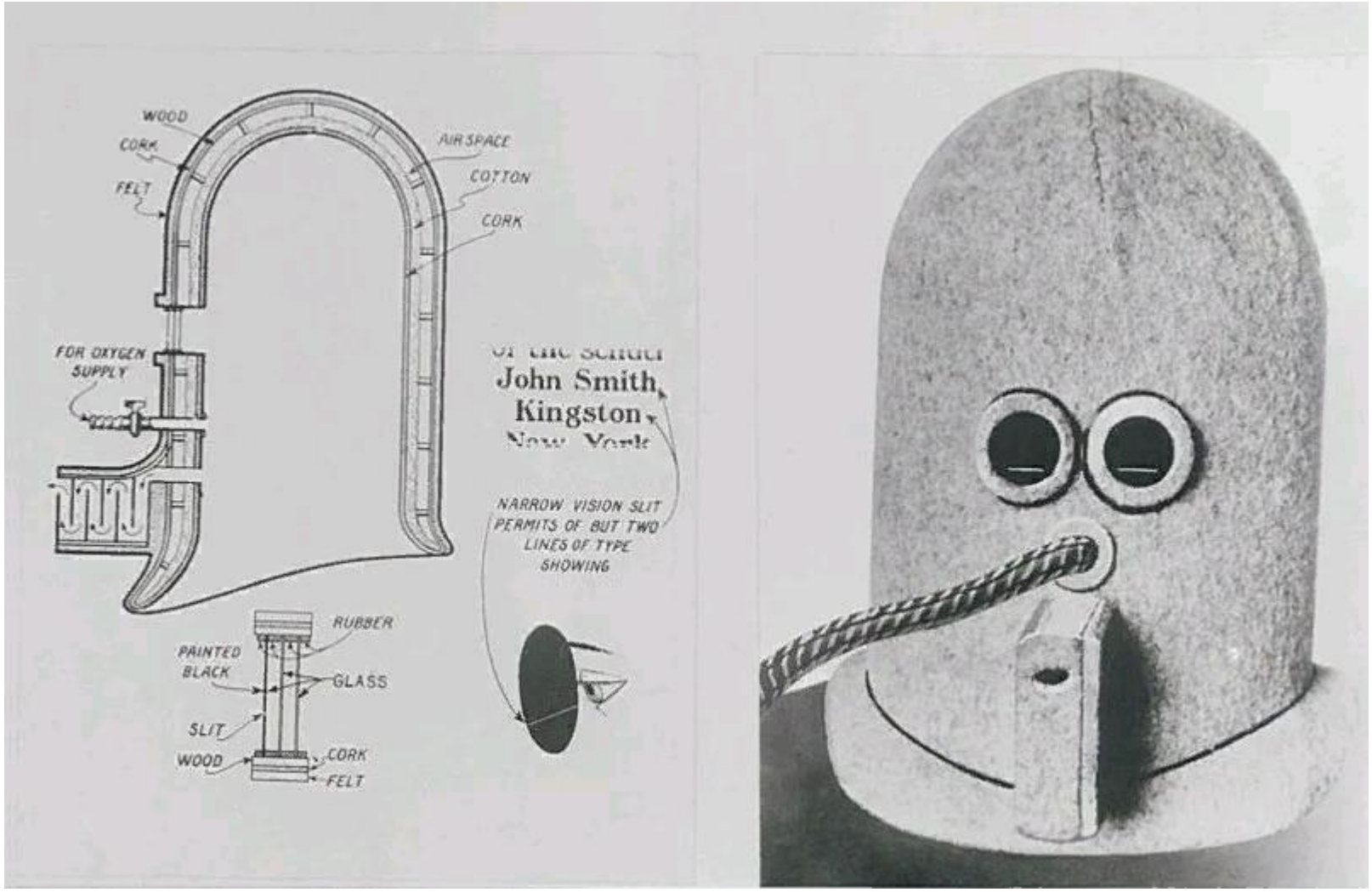
Прибор для сосредоточения

The Isolator

By HUGO GERNSBACK

MEMBER AMERICAN PHYSICAL SOCIETY

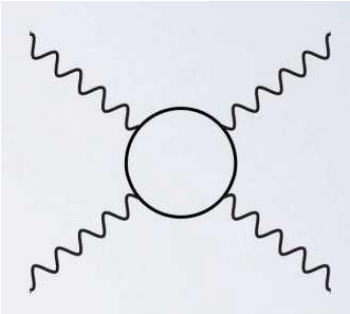
The author at work in his private study aided by the Isolator. Outside noises being eliminated, the worker can concentrate with ease upon the subject at hand.


WOOD
CORK
FELT
AIR SPACE
COTTON
CORK
FOR OXYGEN SUPPLY
John Smith
Kingston
NARROW VISION SLIT PERMITS OF BUT TWO LINES OF TYPE SHOWING
RUBBER
PAINTED BLACK
GLASS
SLIT
WOOD
CORK
FELT

Back-up slides

New physics contributions to γγγZ couplings

New charged particles via loops



$g_i \sim Q^4 m^{-4}$

Example: top partner

Discovery significance (δ = percentage systematic error)

$$S_{\mathrm{dis}} = \sqrt{2}\left[(s+b)\ln\left(\frac{(s+b)(1+\delta^2 b)}{b+\delta^2 b(s+b)}\right) - \frac{1}{\delta^2}\ln\left(1+\frac{\delta^2 s}{1+\delta^2 b}\right)\right]^{1/2}$$

In the limit δ = 0

$$S_{\mathrm{dis}} = \sqrt{2\left[(s+b)\ln\left(1+\frac{s}{b}\right) - s\right]}$$

s << b →

$$S_{\mathrm{dis}} = \frac{s}{\sqrt{b}}$$

S_{dis} ≥ 5 as discovery region