BSM physics at future lepton colliders

Alexander Kisselev

NRC "Kurchatov Institute"-IHEP, Protvino, Russia

(in collaboration with Salih Inan,

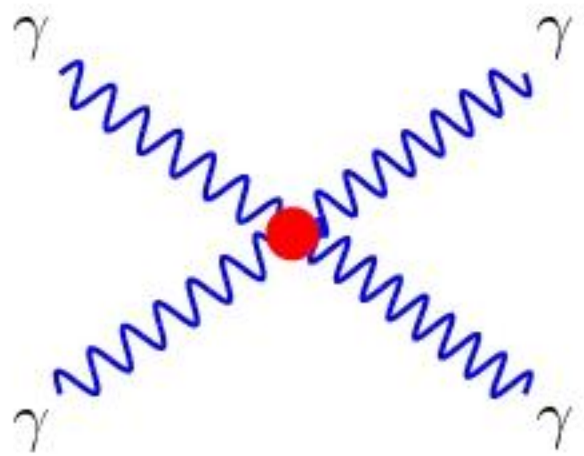
Cumhuriyet University, Sivas, Turkey)

International Conference on Quantum Field Theory, High-Energy Physics, and Cosmology
July 19, 2022, BLTP, JINR

Summary

1. Light-by-light (LBL) scattering $\gamma\gamma \to \gamma\gamma$ of Compton backscattered (CB) photons at high energy collider CLIC. Probing anomalous quartic $\gamma\gamma\gamma\gamma$ couplings
2. Search for anomalous gauge couplings of $\gamma\gamma\gamma Z$ vertex in $\gamma\gamma \to \gamma Z$ collision of CB photons at the CLIC
3. Study of invisible massive dark photon in γe scattering at future lepton colliders ILC, CLIC, and CEPC.
4. Conclusions

Light-by-light scattering of CB photons at the CLIC

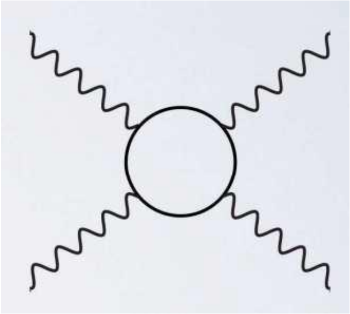


Anomalous diagram for process $\gamma\gamma \rightarrow \gamma\gamma$

The goal is to examine anomalous quartic gauge couplings (QGCs) via reaction $\gamma\gamma \rightarrow \gamma\gamma$ at the CLIC

New physics contributions to 4γ couplings

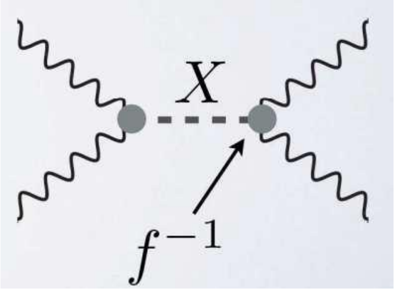
New charged particles via loops



$\zeta_i \sim Q^4\, m^{-4}$

Example: top partner

New neutral particles at tree level

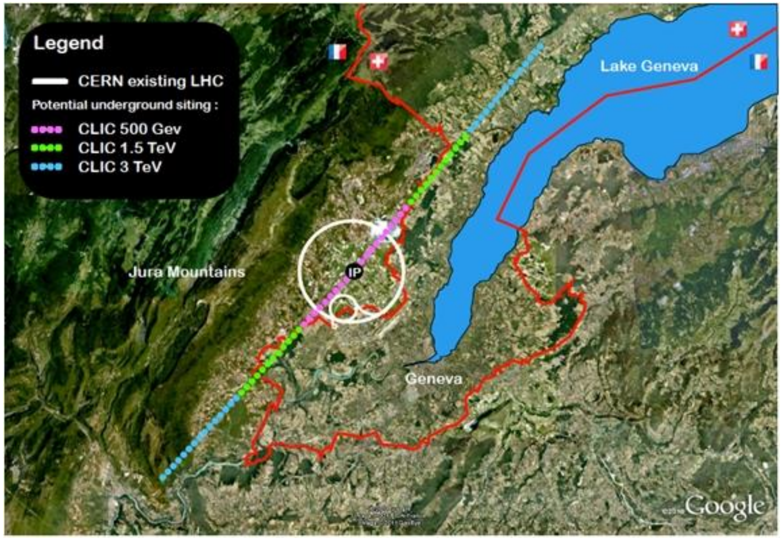


$\zeta_i \sim f^{-2}\, m^{-2}$

Example: KK gravitons, radion (warped extra dimension)

If $f_{KK} \sim$ TeV and $m_{KK} \sim$ few TeV, then $\zeta_i \sim 10^{-2} - 10^{-1}$ TeV^{-4}

Compact Linear Collider (CLIC)



	Collision energy	Integrated luminosity (unpolarized beams)
1st stage	380 GeV	1.0 ab^{-1}
2nd stage	1500 GeV	2.5 ab^{-1}
3rd stage	3000 GeV	5.0 ab^{-1}

λ_0 is helicity of laser photon beam, and λ_e is helicity of electron beam before Compton backscattering

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

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 for LBL scattering

$$\frac{d\sigma}{d\cos\theta} = \frac{1}{128\pi s} \int\limits_{x_{1\,\min}}^{x_{\max}} \frac{dx_1}{x_1} f_{\gamma/e}(x_1) \int\limits_{x_{2\,\min}}^{x_{\max}} \frac{dx_2}{x_2} f_{\gamma/e}(x_2)$$
$$\times \left\{ \left[1 + \xi\left(E_\gamma^{(1)}, \lambda_0^{(1)}\right) \xi\left(E_\gamma^{(2)}, \lambda_0^{(2)}\right)\right] \right.$$
$$\times \left(|M_{++++}|^2 + |M_{++--}|^2\right)$$
$$+ \left[1 - \xi\left(E_\gamma^{(1)}, \lambda_0^{(1)}\right) \xi\left(E_\gamma^{(2)}, \lambda_0^{(2)}\right)\right]$$
$$\left. \times \left(|M_{+-+-}|^2 + |M_{+--+}|^2\right) \right\}$$

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

$\xi(E_\gamma,\lambda_0)$= CB photon helicity

$x_{1,min} = (p_t/E_e)^2$, $x_{2,min} = (p_t/x_1E_e)^2$, $x_{max} = 0.83$

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 γγγγ couplings (in terms of physical fields)

$$L^{\gamma\gamma\gamma\gamma}_{\rm QNGC} = \varsigma_1 (F_{\mu\nu} F^{\mu\nu})(F_{\rho\sigma} F^{\rho\sigma}) + \varsigma_2 (F_{\mu\nu} F^{\nu\rho} F_{\rho\sigma} F^{\sigma\mu})$$

Anomalous couplings ς_1, ς_2 have dimension -4

Numerical analysis

Electron beam helicities:

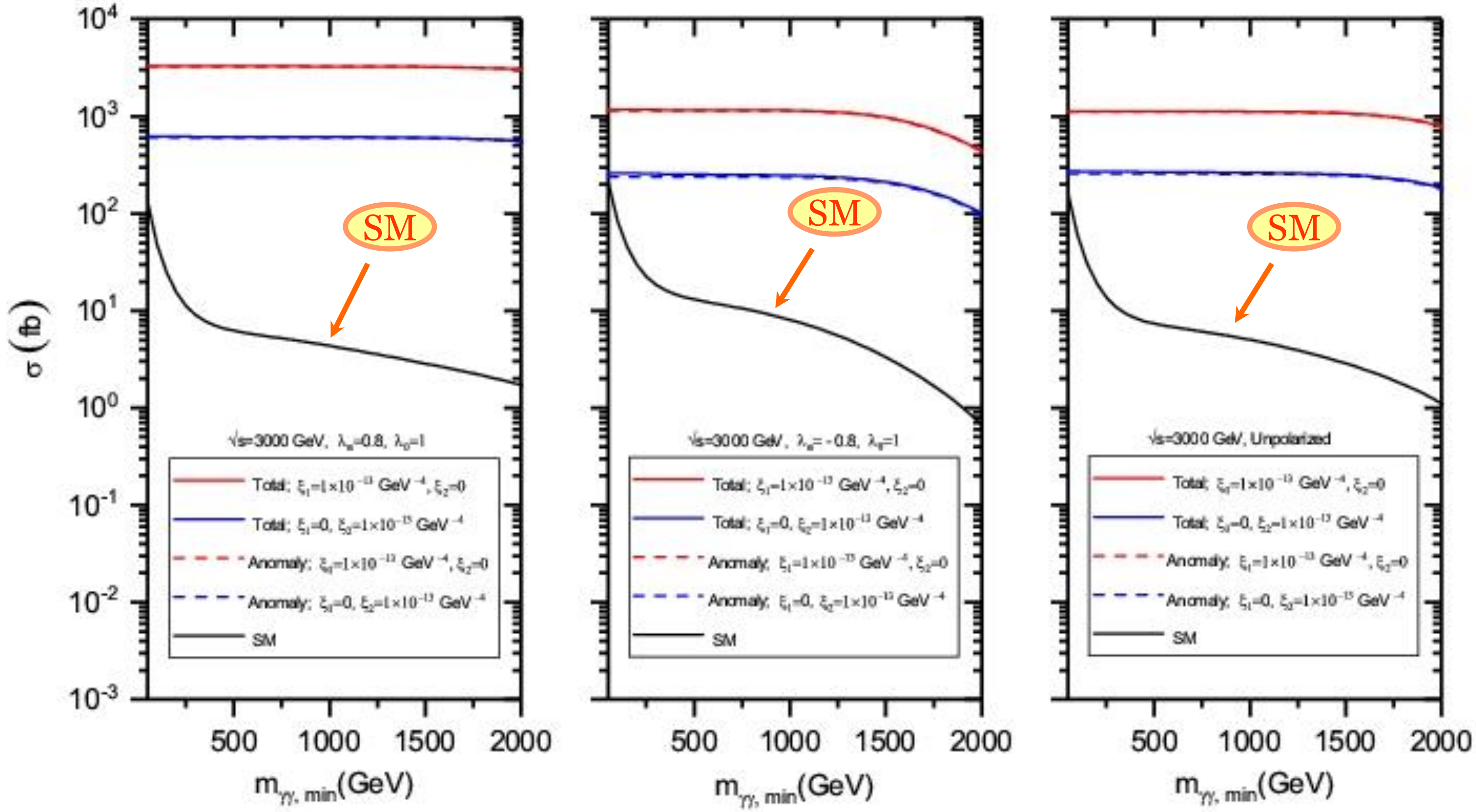
λ_e = 0.8, -0.8, and 0 (unpolarized case)

Cuts on the invariant mass and rapidities of final photons:

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

SM amplitude: *(G.Gounaris et al., EPJC, 9, 673, 1999)*

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



Total cross sections for γγ → γγ scattering versus minimal invariant mass of outgoing photons for √s = 3 TeV. The left, middle and right panels correspond to λ_e= 0.8, -0.8, 0.
The solid curves (from top downwards):
(ς_1 = 10^{-13} GeV^{-4}, ς_2 = 0), (ς_1 = 0, ς_2 = 10^{-13} GeV^{-4}), SM.

Exclusion significance (δ = percentage systematic error)

(Y. Zhang & J. Shen, EPJC, 80, 811, 2020)

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

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

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

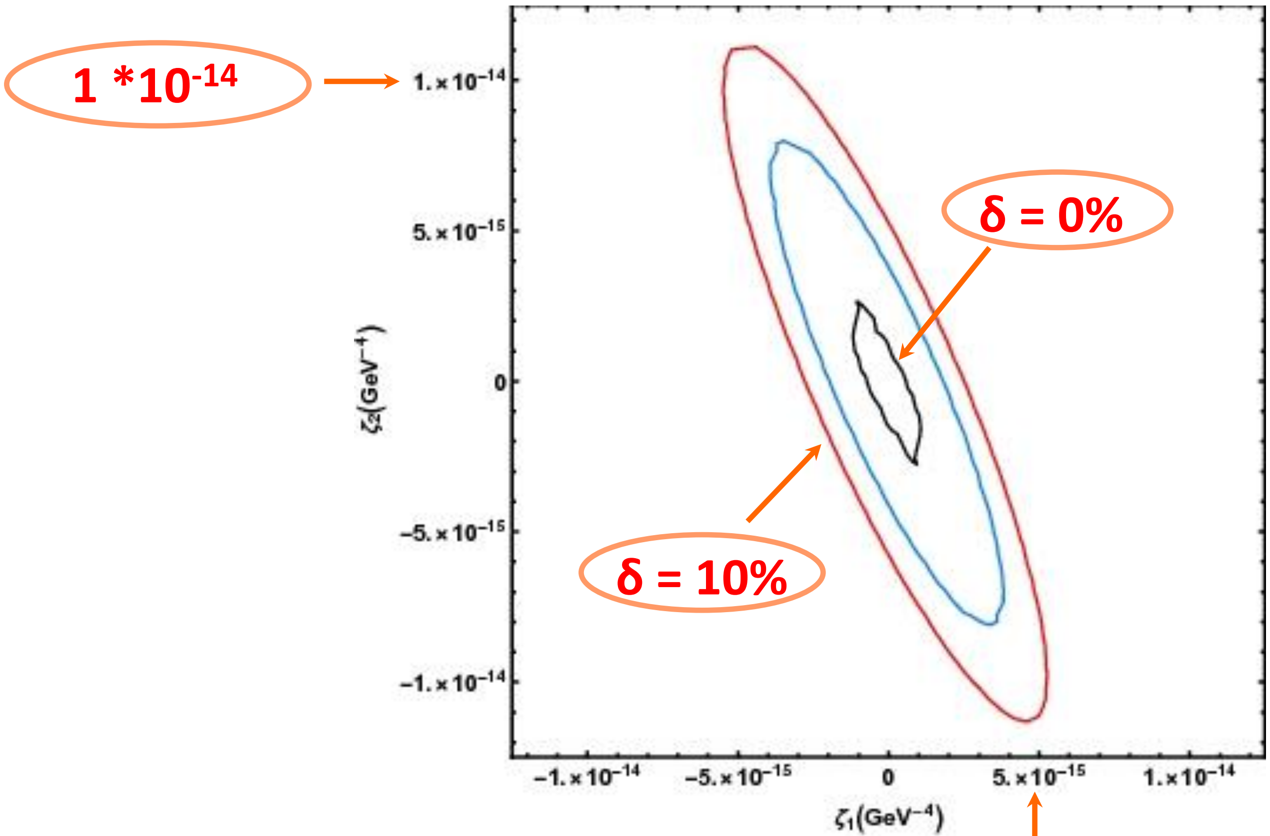
In the limit δ = 0

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

s << b →

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

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



5 *10-15

$|\eta| < 2.5$

$m_{\gamma\gamma} > 1$ TeV

(S.Inan & A.K., EPJC, 81, 664, 2021)

95% C.L. exclusion region for anomalous couplings ς_1, ς_2 for unpolarized LBL scattering at the CLIC. Systematic errors are 0%, 5%, and 10%. The collision energy is 3 TeV, the integrated luminosity is 5 ab^{-1}. Couplings ς_1, ς_2 are in GeV^{-4}.

Exclusion limits on anomalous couplings for the LBL scattering at the CLIC with energy 3.0 TeV

Helicity		0	-0.8	0.8
Luminosity, fb^{-1}		5000	4000	1000
$\lvert\zeta_1\rvert$, GeV^{-4} ($\zeta_2 = 0$)	$\delta = 0\%$	6.85×10^{-16}	8.82×10^{-16}	8.73×10^{-16}
	$\delta = 5\%$	1.90×10^{-15}	2.48×10^{-15}	1.56×10^{-15}
	$\delta = 10\%$	2.63×10^{-15}	3.37×10^{-15}	2.12×10^{-15}
$\lvert\zeta_2\rvert$, GeV^{-4} ($\zeta_1 = 0$)	$\delta = 0\%$	1.43×10^{-15}	1.85×10^{-15}	1.82×10^{-15}
	$\delta = 5\%$	3.99×10^{-15}	5.12×10^{-15}	3.28×10^{-15}
	$\delta = 10\%$	5.53×10^{-15}	7.10×10^{-15}	4.46×10^{-15}

(S.Inan & A.K., EPJC, 81, 664, 2021)

Bounds on anomalous couplings for LHC and HL-LHC

LHC, L=300 fb^{-1} :
$|\varsigma_1| < 1.5*10^{-14}$ GeV^{-4}, $|\varsigma_2| < 3.0*10^{-14}$ GeV^{-4}

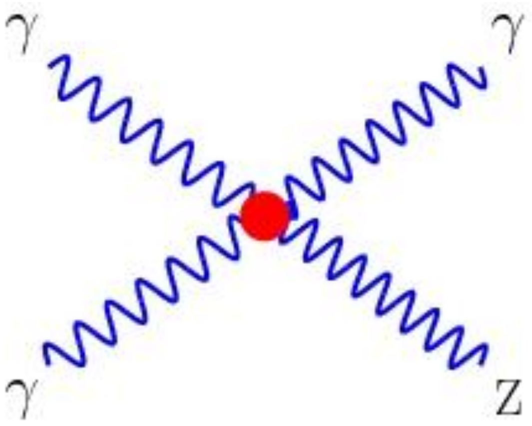
(S.Fichet et al., JHEP 02, 165, 2015)

HL-LHC, L=3000 fb^{-1} :
$|\varsigma_1| < 7.0*10^{-15}$ GeV^{-4}, $|\varsigma_2| < 1.5*10^{-14}$ GeV^{-4}

(S.Fichet et al., Phys. Rev. D 89, 114004, 2014)

γZ production in photon-photon scattering

Anomalous diagram for process $\gamma\gamma \to \gamma Z$



$Z \to e, \mu$

Effective Lagrangian for anomalous γγγZ couplings

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

Anomalous couplings g_1, g_2 have dimension -4

Feynman rule for anomaly vertex γγγZ

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

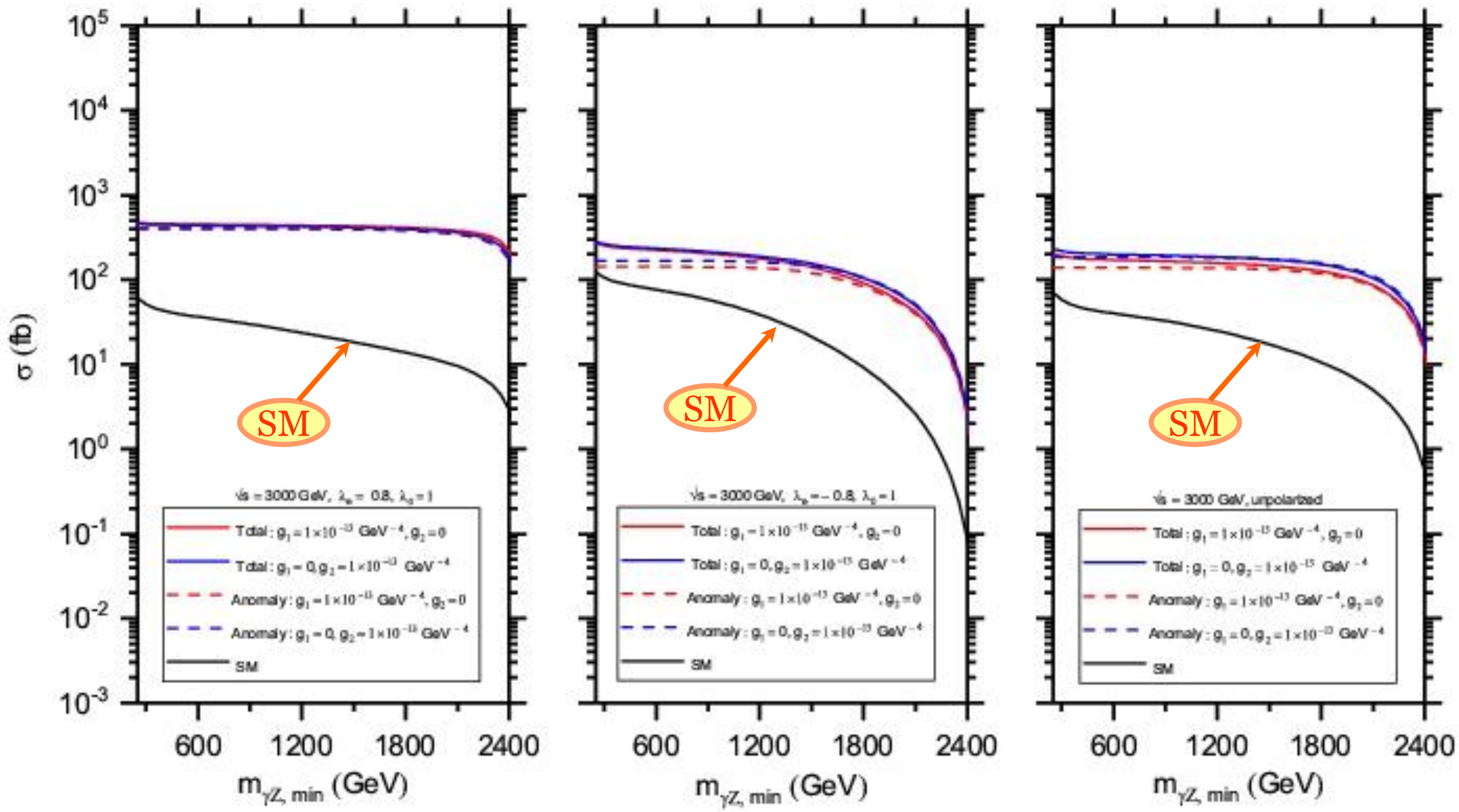
$\mathcal{P}$ – permutations (symmetrization with respect to photon’s momenta and indices)

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

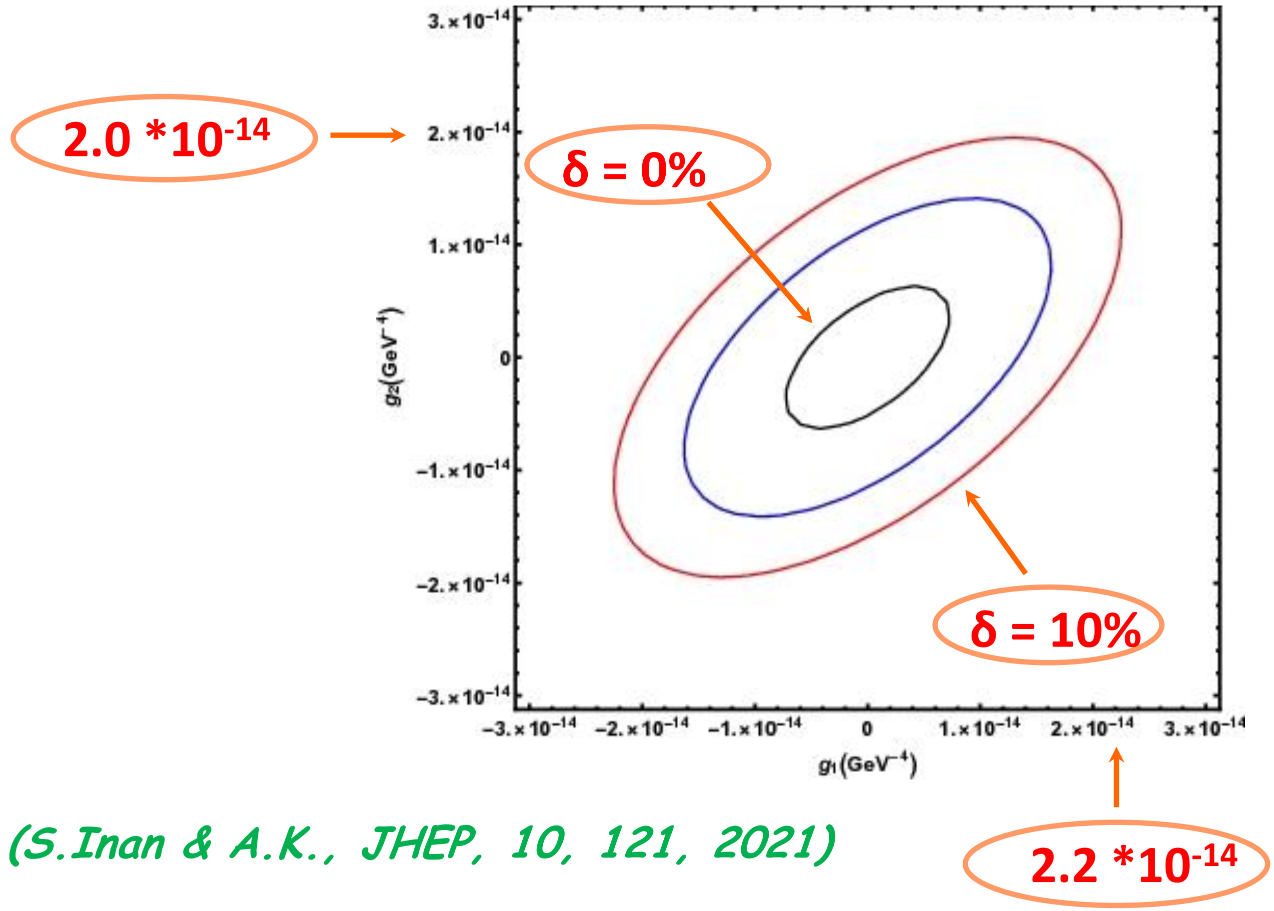
→ 24 helicity amplitudes proportional to g_1
24 helicity amplitudes proportional to g_2

(S.Inan & A.K., JHEP, 10, 121, 2021)

SM amplitudes are taken from *G.Gounaris et al., EPJC, 10, 499, 1999*



Total cross sections for γγ → γZ scattering versus minimal invariant mass of outgoing photons for √s = 3 TeV. The left, middle and right panels correspond to λ_e= 0.8, -0.8, 0. Solid curves correspond to (g_1 = 10^{-13} GeV^{-4}, g_2 = 0), SM.



|η| < 2.5

$m_{\gamma Z}$ > 1 TeV

(S.Inan & A.K., JHEP, 10, 121, 2021)

95% C.L. exclusion region for anomalous couplings g_1, g_2 for unpolarized γγ → γZ scattering at the CLIC. Systematic errors are 0%, 5%, and 10%. The collision energy is 3 TeV, the integrated luminosity is 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. Polarized case

λ_e		0	-0.8	0.8
L, fb^{-1}		5000	4000	1000
$\|g_1\|$, 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}
$\|g_2\|$, 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}

(S.Inan & A.K., JHEP, 10, 121, 2021)

Bounds on anomalous couplings for the LHC and HL-LHC

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

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

→ $|f_i| < 1.3*10^{-9}$ GeV^{-4} where $f_i = g_i/8$

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

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

HL-LHC, L=3000 fb^{-1} :
$|f_i| < 7.8*10^{-14}$ GeV^{-4}

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

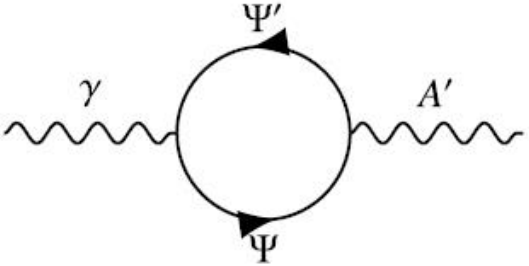
Invisible dark photons in γe scattering at future lepton colliders ILC, CLIC, CEPC

We consider dark matter (DM) scenario in which **no** DM are charged under SM gauge group

Lightest stable DM particles can only interact with SM through exchange of massive vector mediator, dark photon (DP) A'

DP kinematically mixes with SM $U(1)_Y$ hypercharge gauge field (kinematic mixing portal)

Such mixing can be generated by loops of massive particles charged under both $U(1)_Y$ and secluded U(1)' groups



Gauge Lagrangian

$$\mathcal{L}_{\text{gauge}} = -\frac{1}{4}B_{\mu\nu}B^{\mu\nu} - \frac{1}{4}\bar{F}'_{\mu\nu}\bar{F}'^{\mu\nu} - \frac{\varepsilon}{2c_W}\bar{F}'_{\mu\nu}B^{\mu\nu}$$

$B_{\mu\nu}, \bar{F}'_{\mu\nu}$ are field strength tensors of $U(1)_Y, U(1)'$

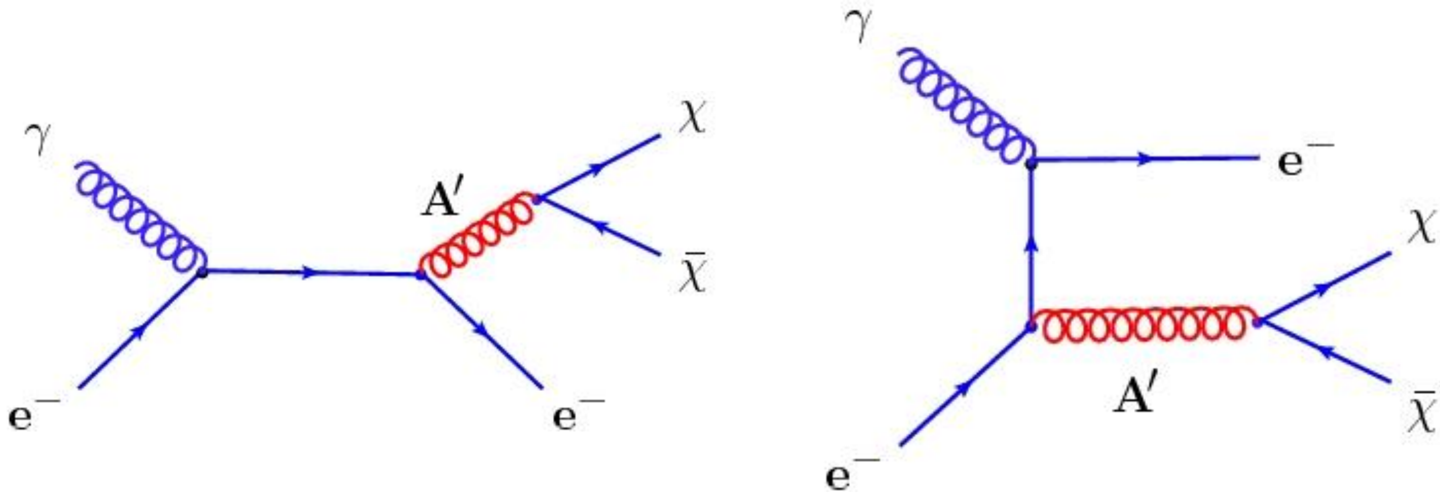
ε – kinetic mixing parameter

Interaction Lagrangian

(*after diagonalizaion of gauge and DP fields*)

$$\mathcal{L}_{\text{int}} = eJ_\mu A^\mu - \varepsilon e J_\mu A'^\mu + \varepsilon e' t_W J'_\mu Z_\mu + e' J'_\mu A'^\mu + \mathcal{L}_{A'\chi}$$

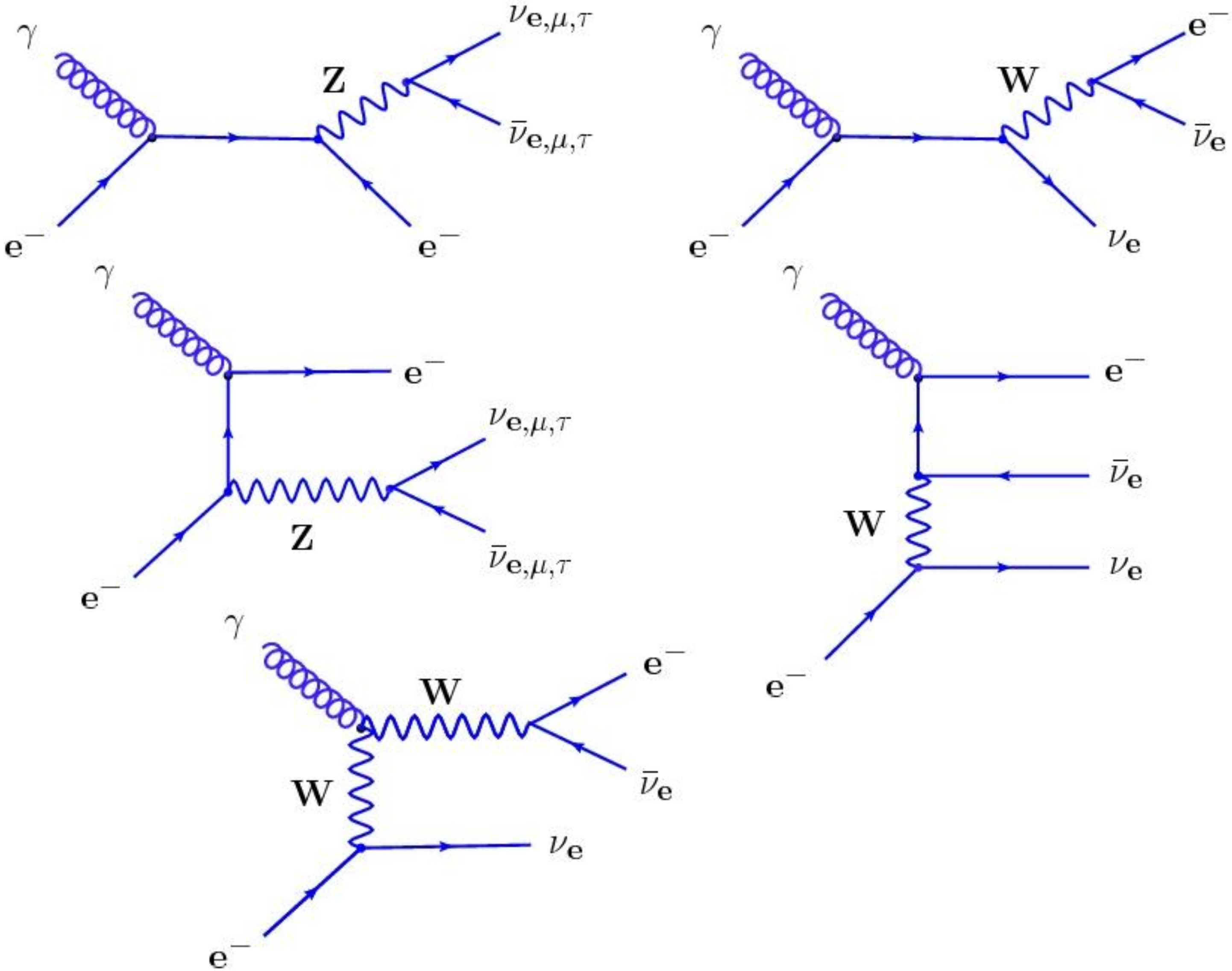
Production of DP in γe⁻ collision with subsequent invisible decay



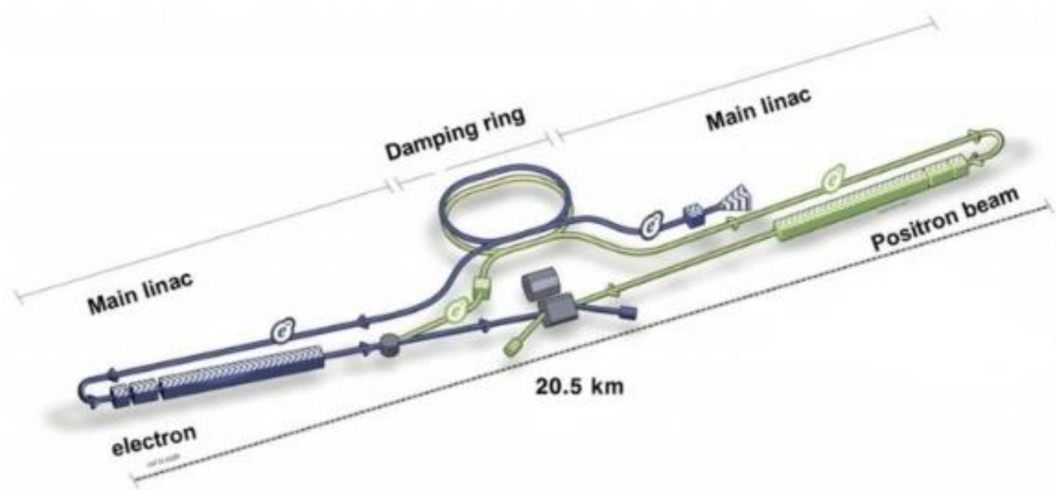
χ – dark matter particle

We assume that $\mathcal{B}$(A' → χ bar(χ)) = 1

SM background $\gamma e^- \to e^- + \nu + bar(\nu)$



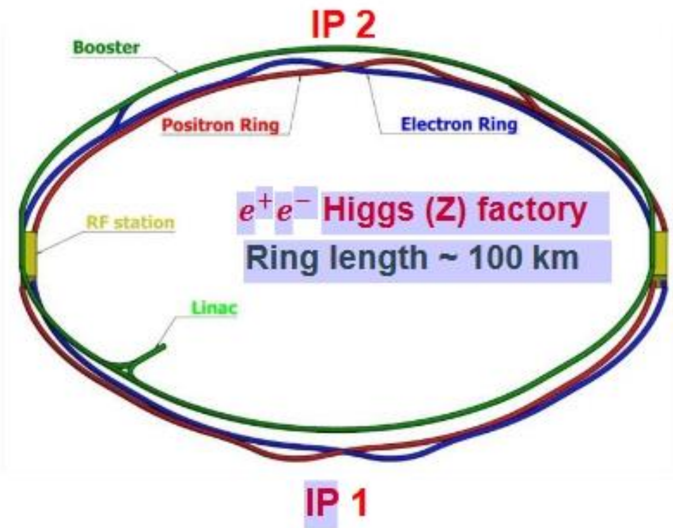
International Linear Collider (ILC)

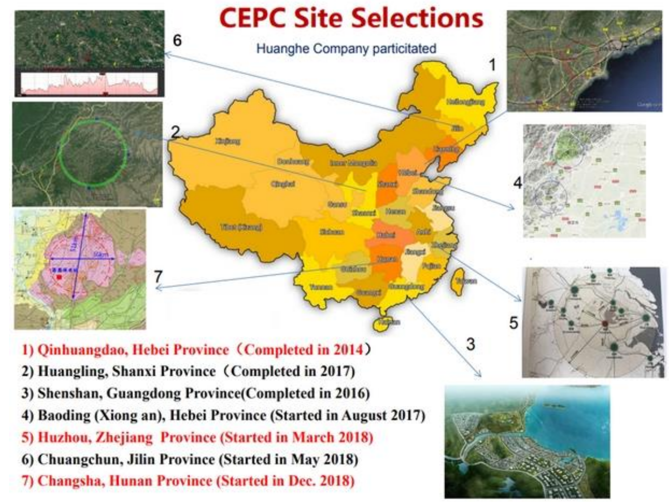


	Collision energy	Integrated luminosity (unpolarized beams)
1st stage	250 GeV	2.0 ab^{-1}
2nd stage	500 GeV	4.0 ab^{-1}
3rd stage	1000 GeV	5.4 ab^{-1}

(ILC Technical Design Report, arXiv:1306.6327, 1903.01629)

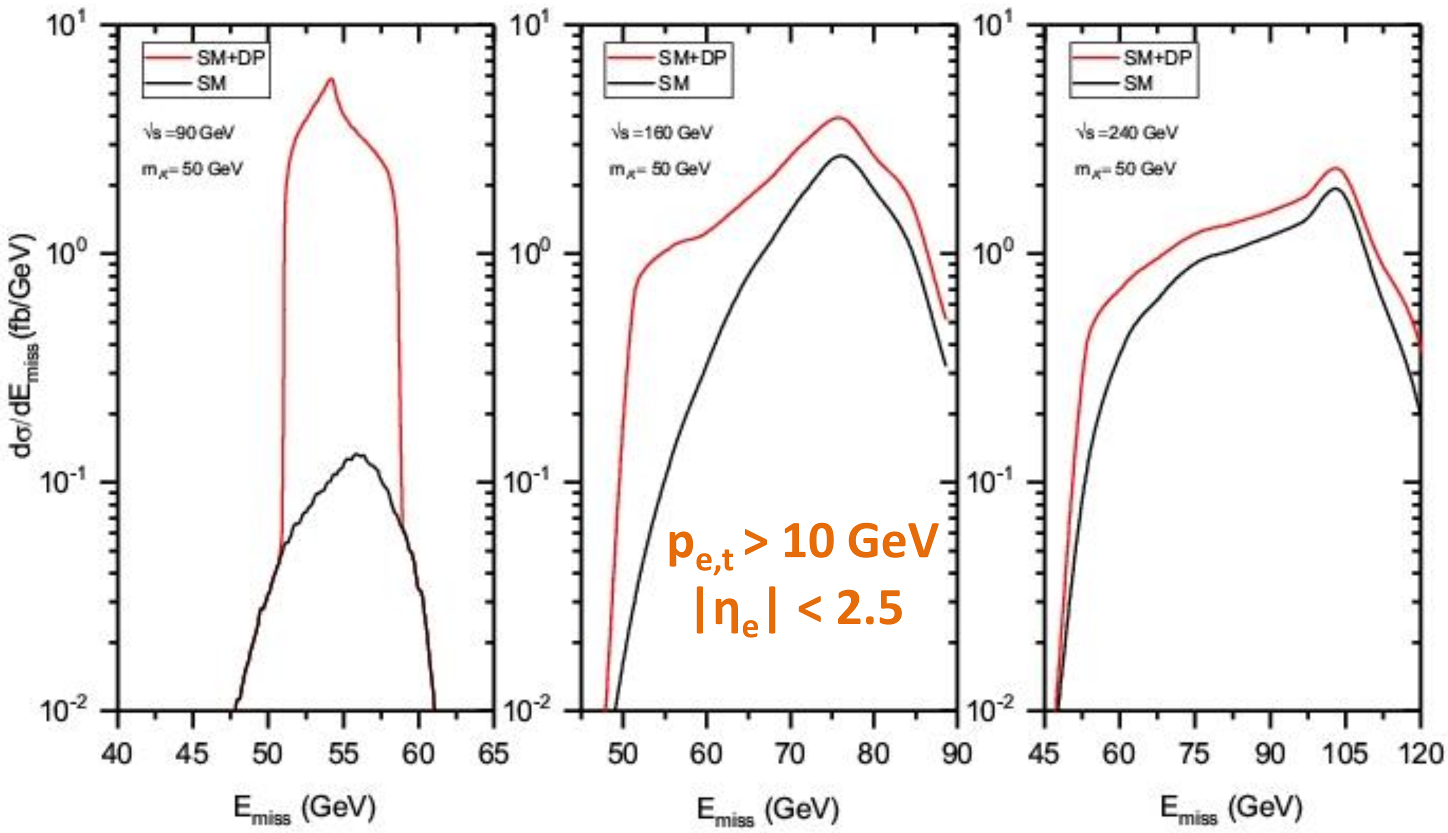
Circular Electron Positron Collider (CEPC)



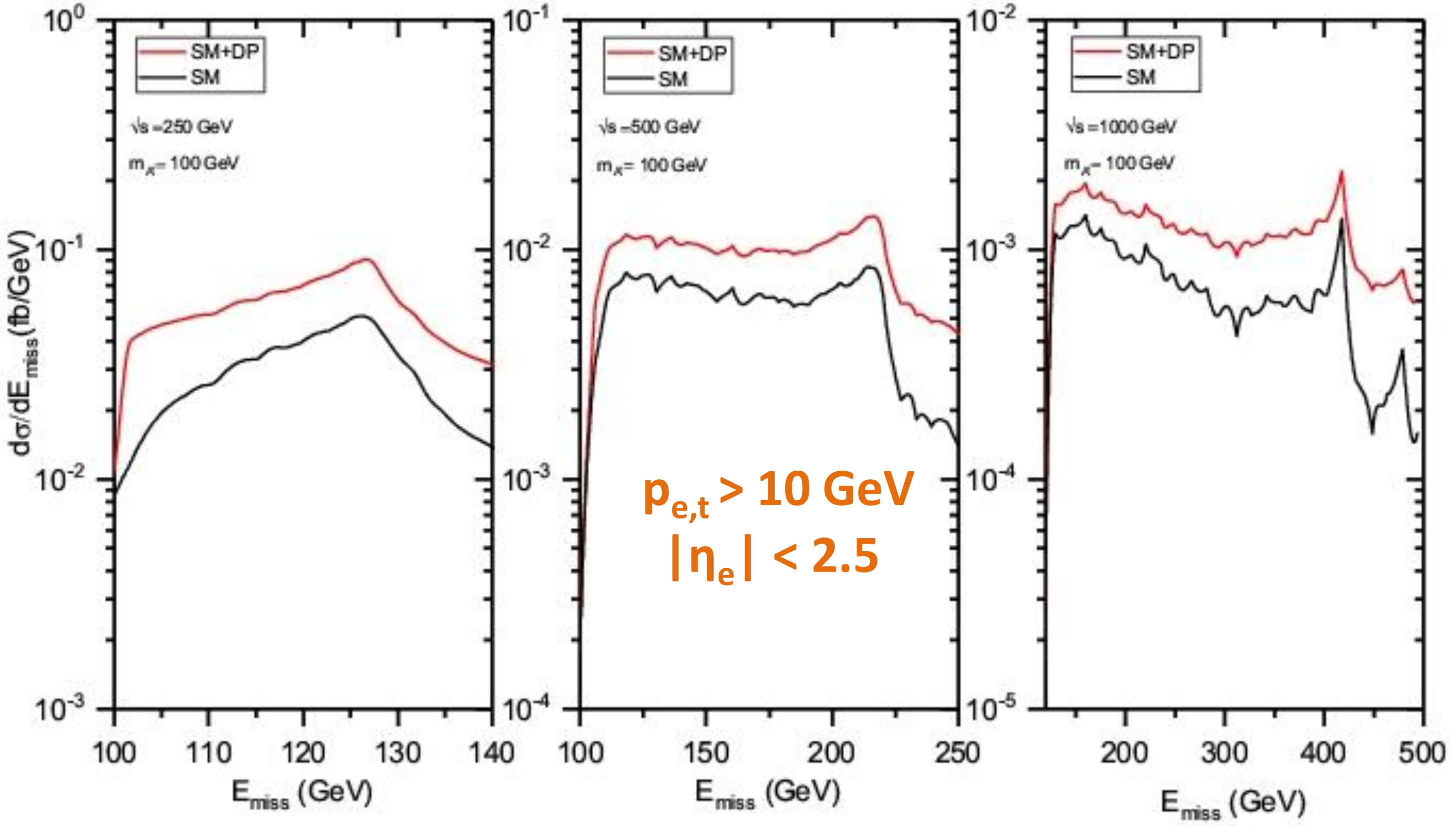


	Collision energy	Integrated luminosity (unpolarized beams)
1st stage	90 GeV	16 ab^{-1}
2nd stage	180 GeV	2.6 ab^{-1}
3rd stage	240 GeV	5.6 ab^{-1}

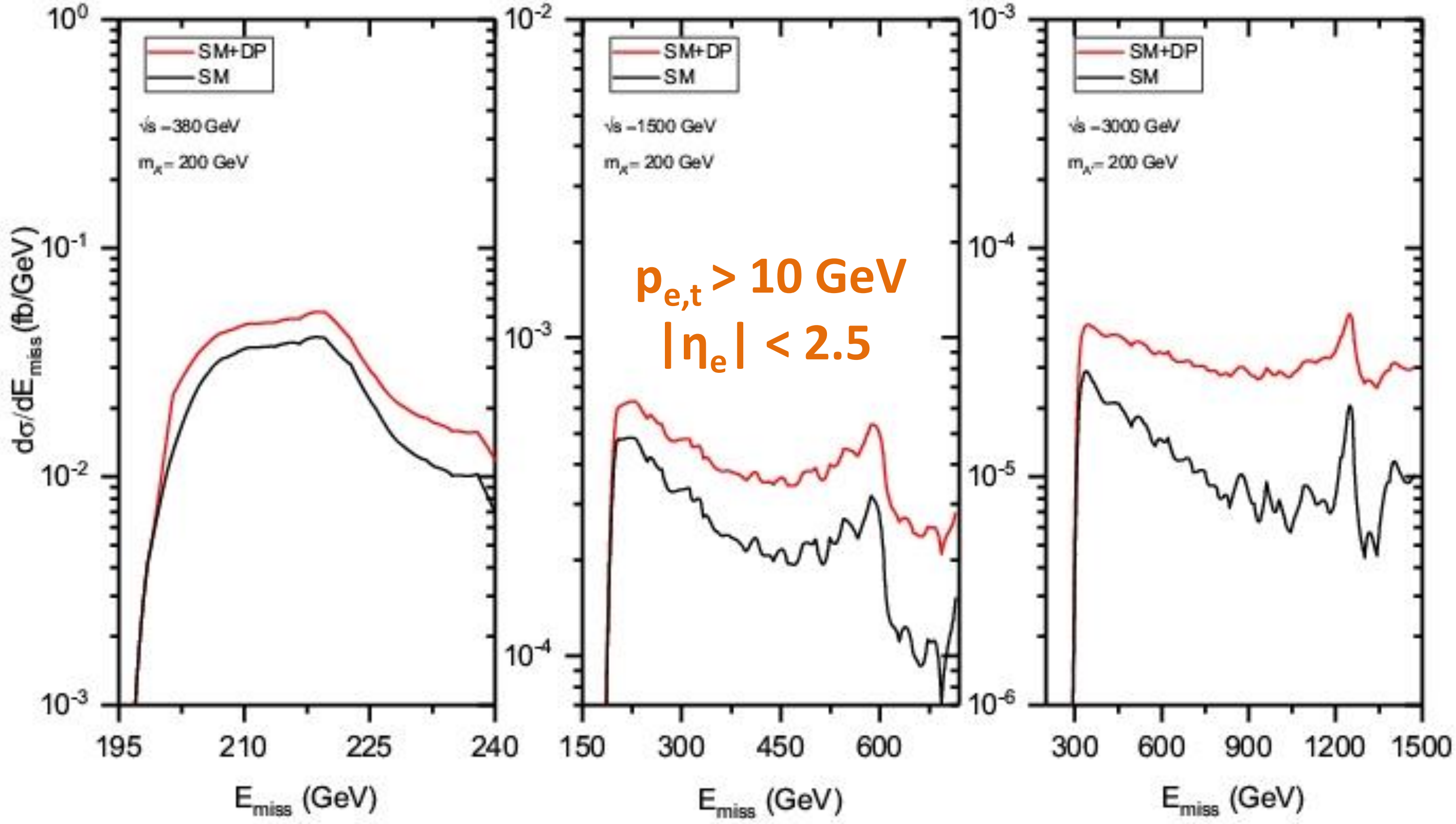
(CEPC Study Group, arXiv:1809.00285, 1811.10545)



Differential cross sections for $\gamma e^- \to e^- + E_{miss}$ scattering at the collider CEPC. DP mass is $m_{A'}$ = 50 GeV, mixing parameter is ε = 0.1. Black curves are SM predictions.

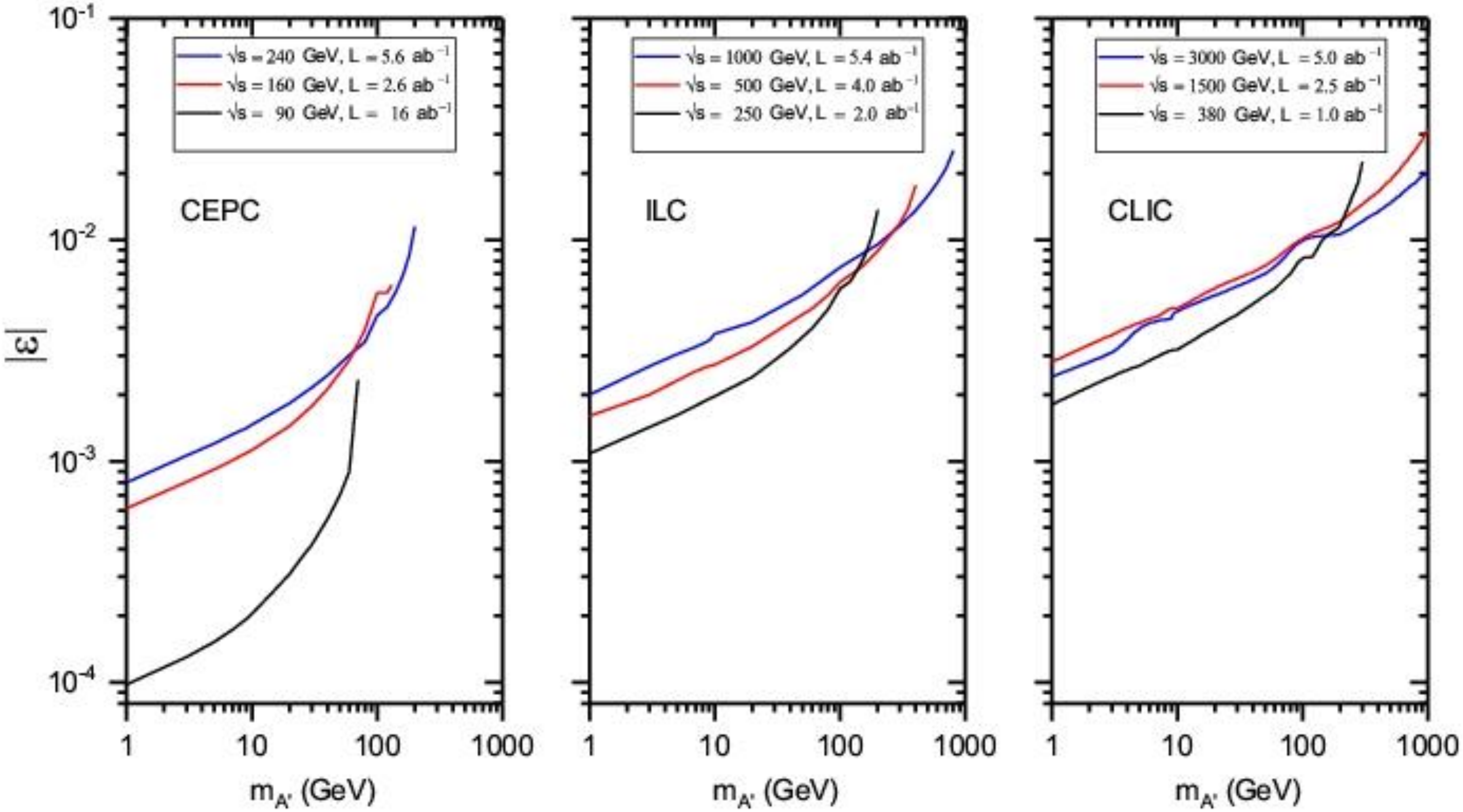


Differential cross sections for $\gamma e^- \rightarrow e^- + E_{miss}$ scattering at the collider ILC. DP mass is $m_{A'}$ = 100 GeV, mixing parameter is ε = 0.1. Black curves are SM predictions.



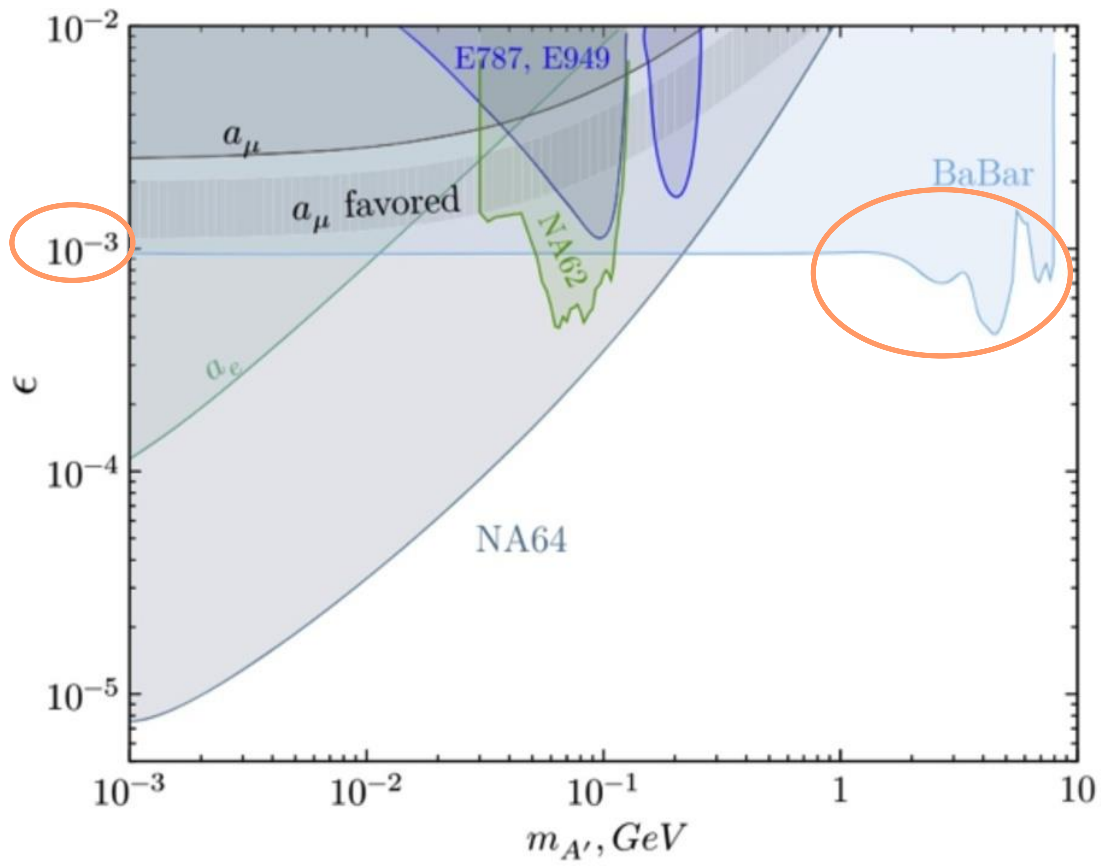
Differential cross sections for $\gamma e^- \rightarrow e^- + E_{miss}$ scattering at the collider CLIC. DP mass is $m_{A'} = 200$ GeV, mixing parameter is $\varepsilon = 0.1$. Black curves are SM predictions.

(S.Inan & A.K., EPJC, 82, 592, 2022)



Excluded bounds at 95% C.L. on DP mass $m_{A'}$ and mixing parameter ε for invisible DP production in $\gamma e^- \rightarrow A'e^-$ *unpolarized* scattering at future lepton colliders

$p_{e,t} > 10$ GeV, $|\eta_e| < 2.5$, $|m_{A'} - m_{miss}| < 10$ GeV



Exclusion limits on mixing parameter ε
for massive DP going into invisible states

(A. Filippi & M. De Napoli, Rev. Phys. 5, 100042, 2020)

Conclusions

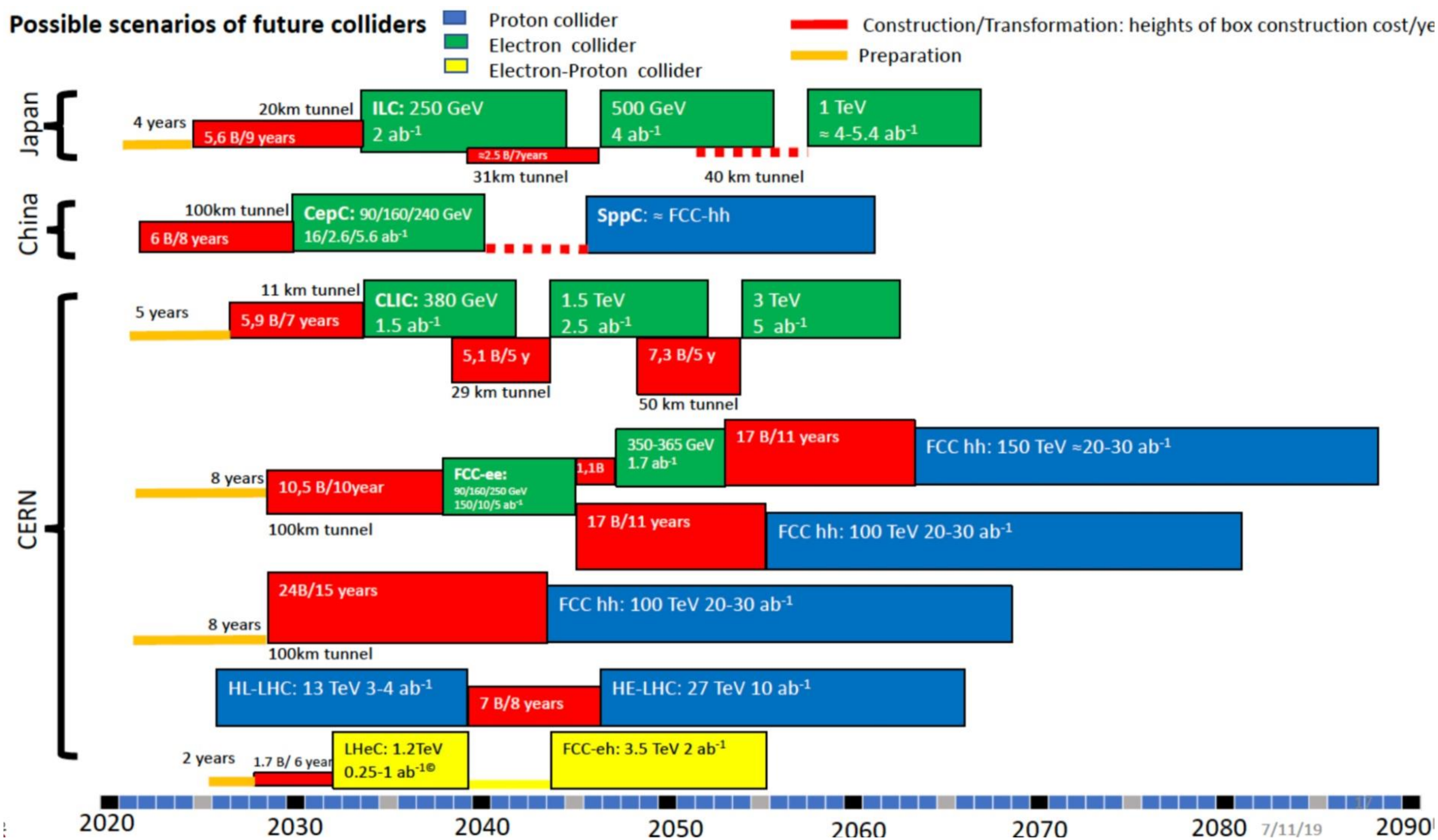
- We have studied anomalous quartic neutral gauge couplings in unpolarized and polarized LBL scattering of CB photons at 3 TeV CLIC
- Exclusion regions for these couplings are obtained. Our best constraints are $\varsigma_1 = 6.9*10^{-4}$ TeV^{-4} and $\varsigma_2 = 1.4*10^{-3}$ TeV^{-4}, one order of magnitude stronger than the HL-LHC bounds derived for integrated luminosity of 3 ab^{-1}
- Sensitivity to anomalous couplings of the γγγZ vertex is examined using CB photon scattering $\gamma\gamma \to \gamma Z$ at 3 TeV CLIC. For both couplings, g_1 and g_2, our best bound is $5*10^{-3}$ TeV^{-4}, while the HL-LHC bounds are $(1-0.7)*10^{-1}$ TeV^{-4}

- For the first time, production of the massive DP in γe scattering at future lepton colliders ILC, CLIC and CEPC is studied
- Invisible decay mode of DP is addressed. Wide range, 1 GeV – 1 TeV, of DP mass $m_{A'}$ is considered. We have obtained exclusion regions in the plane $(m_{A'}, \varepsilon)$, where ε is the kinetic mixing parameter
- In low mass region, 1-10 GeV, our bounds on ε for the 90 CEPC are several times stronger than BaBar limit (~ 10^{-3}). The CEPC bounds for 160 and 240 GeV, as well as bounds for the 250 ILC are close to the BaBar constraints

Thank you for your attention

Back-up slides

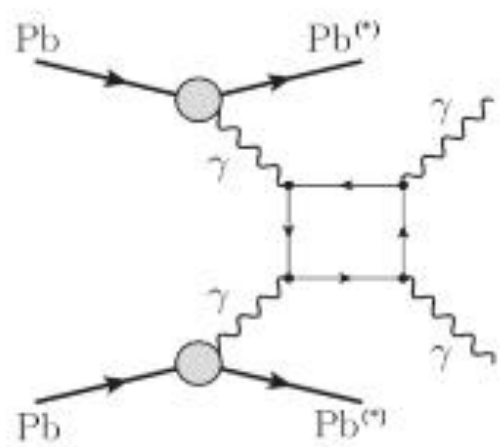
Possible scenario of future colliders



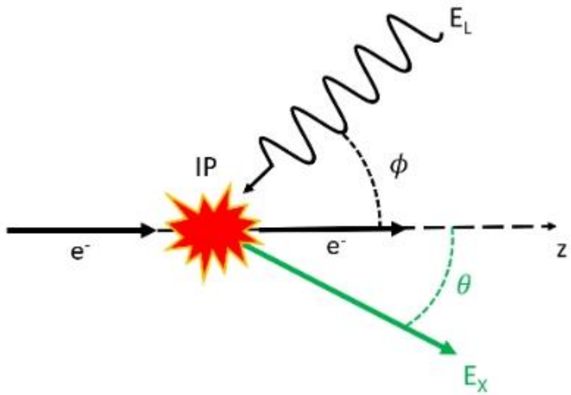
Anomalous γγγγ vertex

The first evidence of γγ → γγ process was observed by ATLAS & CMS in Pb-Pb collisions

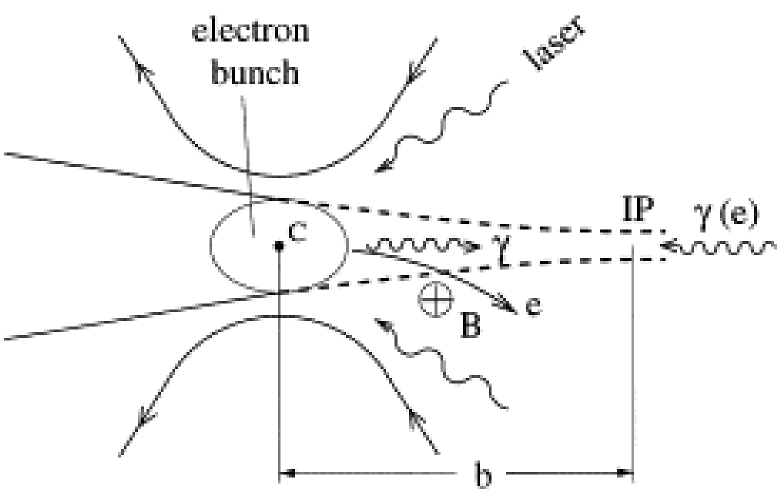
(ATLAS Collab., Nat. Phys., 13, 852, 2017)
(CMS Collab., Phys. Rev. Lett. 123, 052001, 2019)



Inverse laser-Compton scattering process



Scheme of γγ (γe) collider



Helicity of CB photon

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

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

Spectrum of CB photons

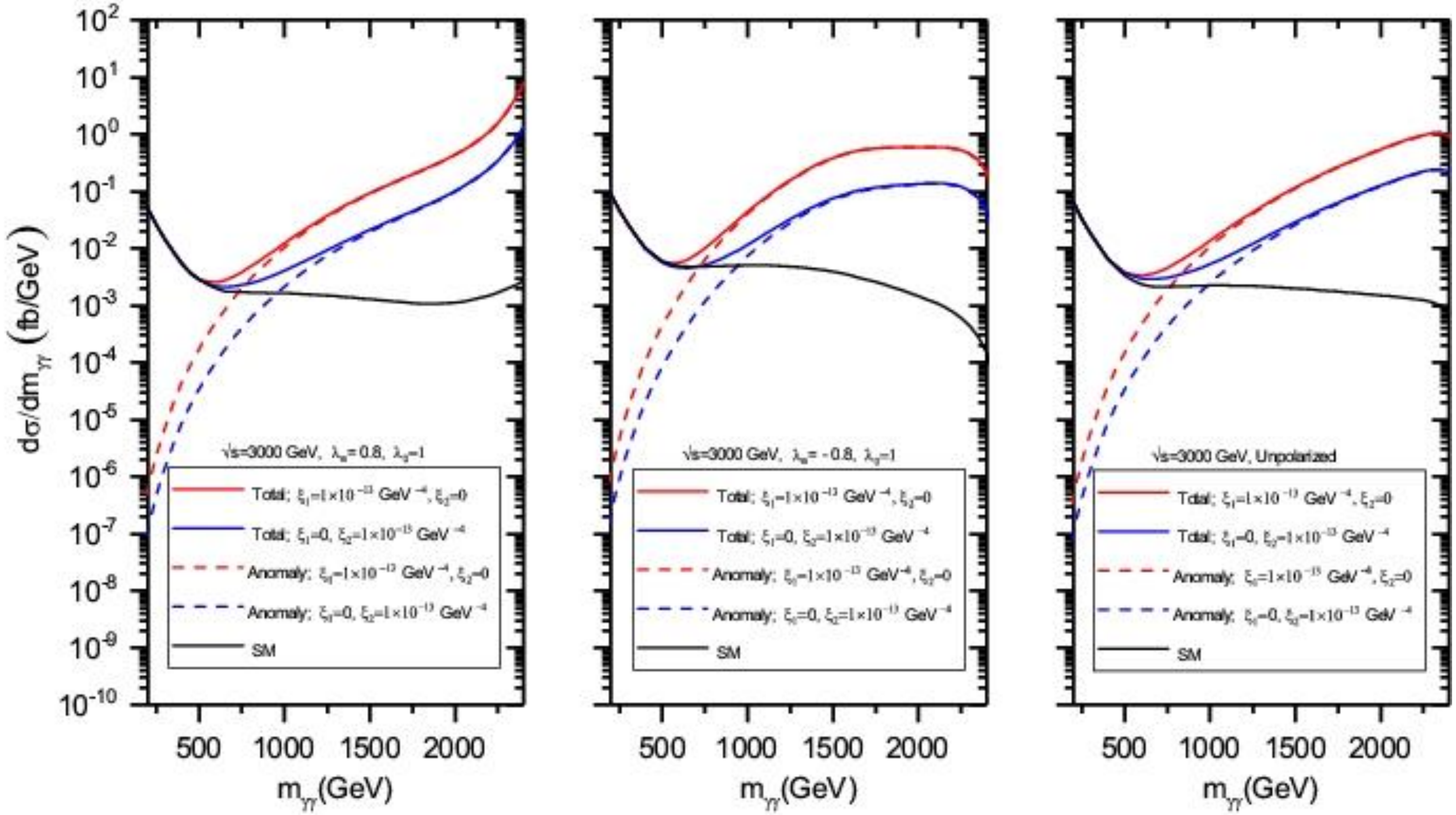
$$f_{\gamma/e}(x) = \frac{1}{g(\zeta)}\left[1 - x + \frac{1}{1-x} - \frac{4x}{\zeta(1-x)} + \frac{4x^2}{\zeta^2(1-x)^2} + \lambda_0\lambda_e r\zeta(1-2r)(2-x)\right],$$

where

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

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

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



Differential cross sections for the process $\gamma\gamma \rightarrow \gamma\gamma$ versus invariant mass of outgoing photons at $\sqrt{s}$ = 3 TeV. The left, middle and right panels correspond to λ_e= 0.8, -0.8, 0.

Solid curves (from top downwards):

($\varsigma_1 = 10^{-13}$ GeV^{-4}, $\varsigma_2 = 0$), ($\varsigma_1 = 0$, $\varsigma_2 = 10^{-13}$ GeV^{-4}), SM.

Discovery significance (δ = percentage systematic error)

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

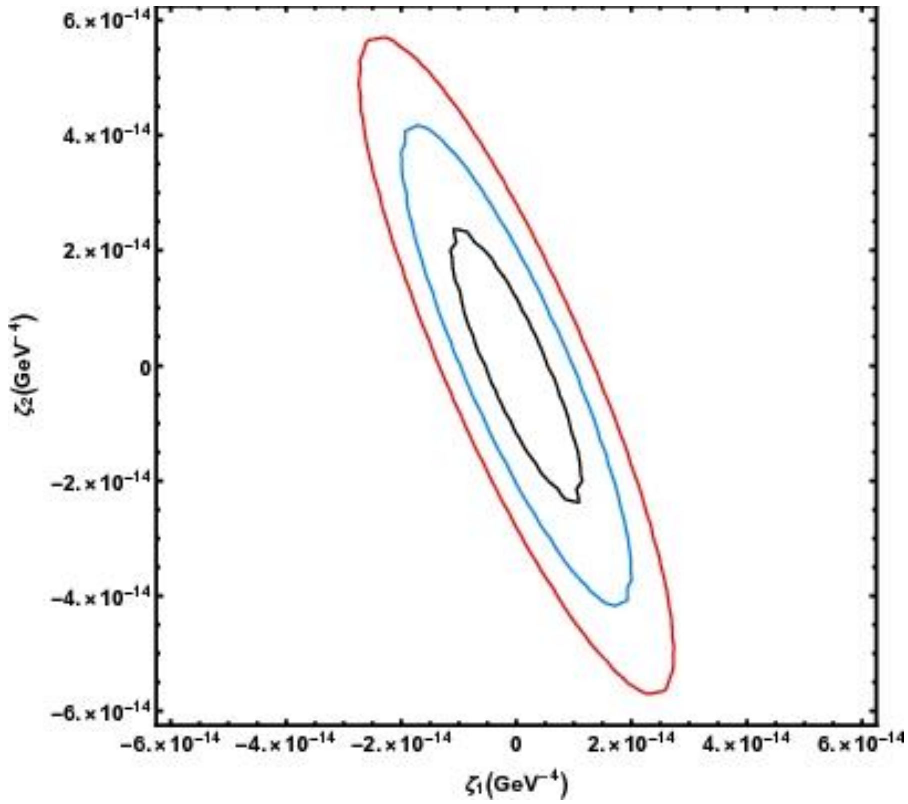
In the limit $\delta = 0$

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

$s \ll b$ →

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

$S_{\rm dis} \geq 5$ as discovery region



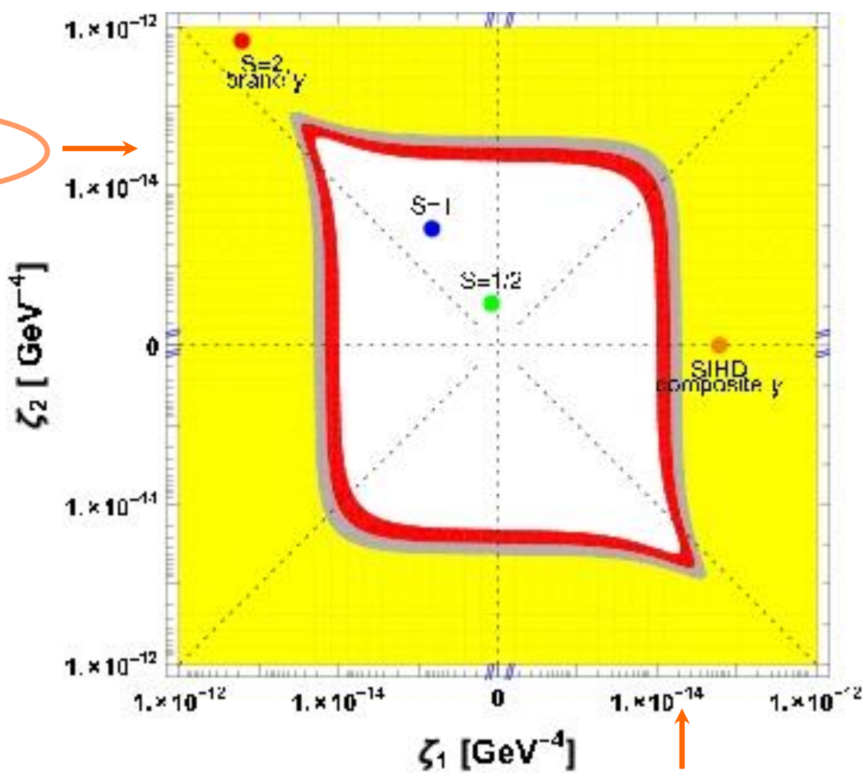
$|\eta_{\gamma\gamma}| < 2.5$
$m_{\gamma\gamma} > 1$ TeV

95% C.L. exclusion region for anomalous couplings ζ_1, ζ_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}. Couplings ζ_1, ζ_2 are in GeV^{-4}.

(S.Inan & A.K., EPJC, 81, 664, 2021)

Bounds on anomalous couplings for LHC

(S.Fichet et al., JHEP 02, 165, 2015)



3 $*10^{-14}$

2 $*10^{-14}$

Anomalous $\gamma\gamma\gamma Z$ vertex

Another effective Lagrangian for anomalous γγγZ couplings

$$L_{\gamma\gamma\gamma Z} = \tilde{g}_1 (F_{\mu\nu} F^{\mu\nu})(F_{\rho\sigma} Z^{\rho\sigma}) + \tilde{g}_2 (F_{\mu\nu} \tilde{F}^{\mu\nu} F_{\rho\sigma} \tilde{Z}^{\rho\sigma})$$

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

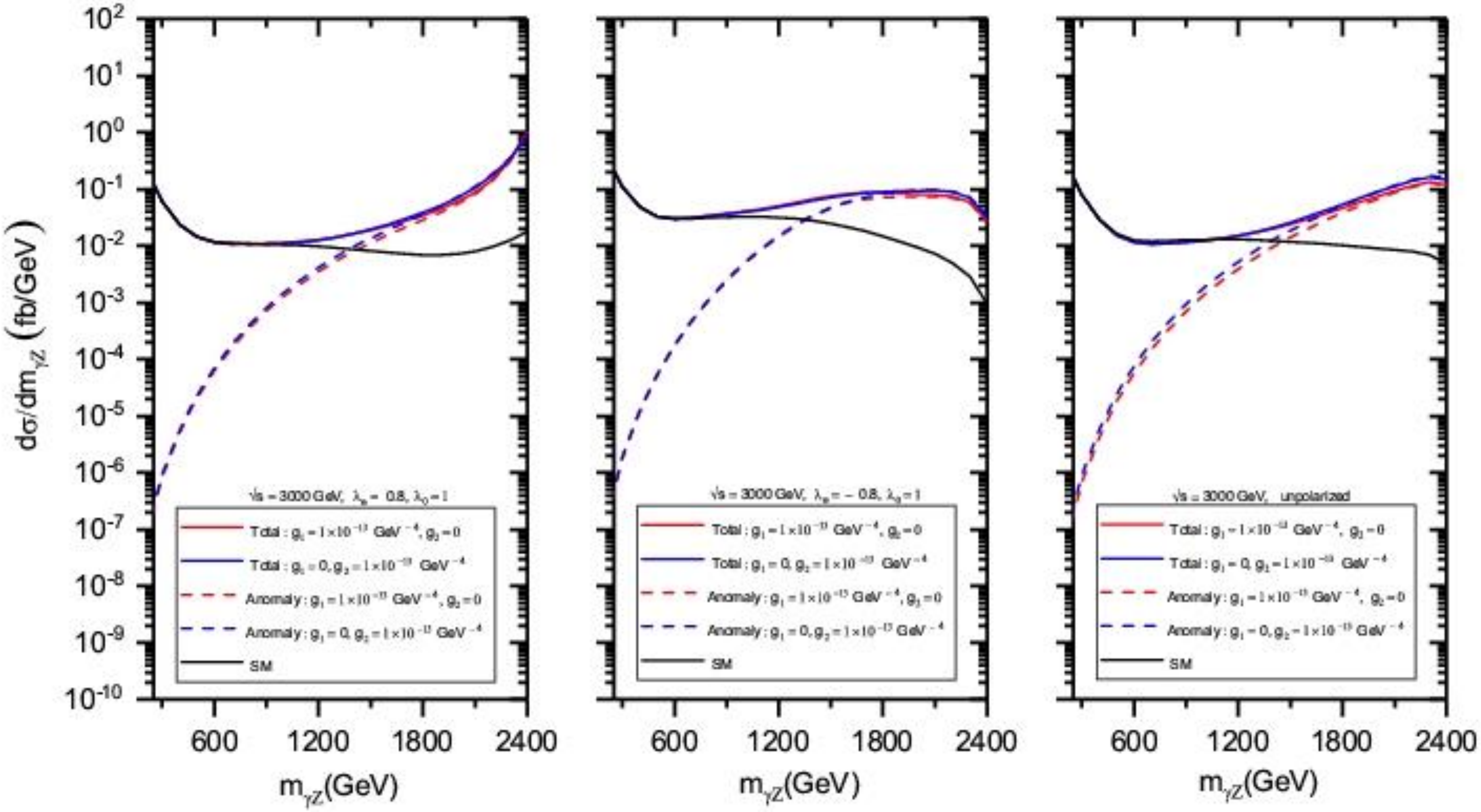
→ **Relations between two sets of coupling constants**

$$g_1 = 8(\tilde{g}_2 - \tilde{g}_1), \quad g_2 = 8\tilde{g}_2$$

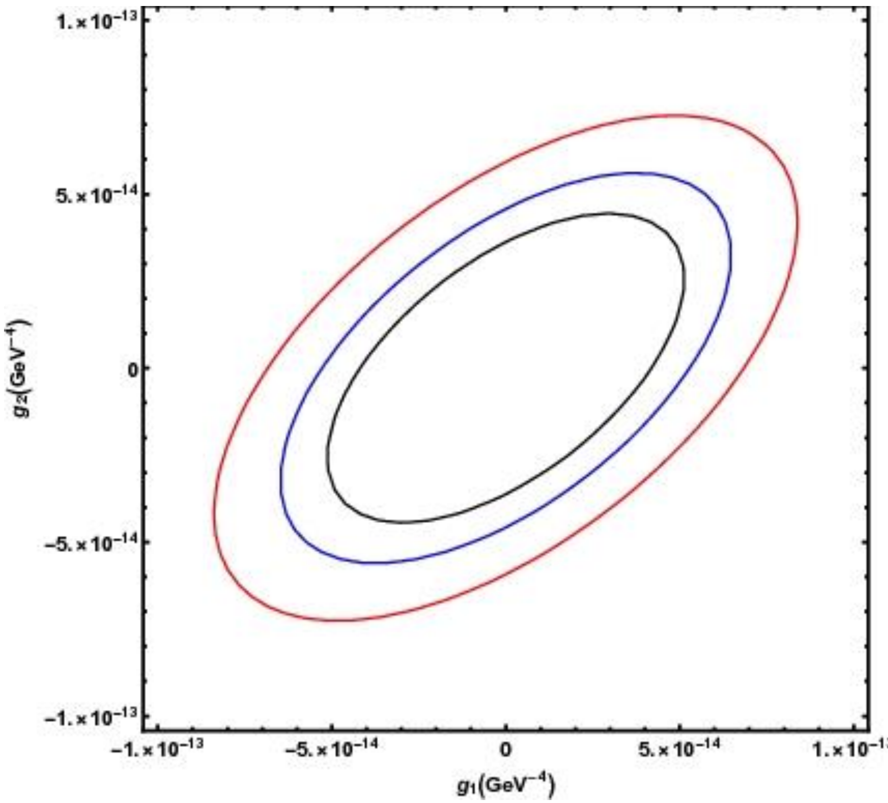
Unpolarized case

$$\sum_{\lambda_1 \ldots \lambda_4} |M_{\lambda_1\lambda_2\lambda_3\lambda_4}|^2 = \frac{1}{4}[g_1^2(3A + 2B) - 4g_1 g_2(A + B) + 4g_2^2(A + B)]$$

$$A = s^2t^2 + t^2u^2 + u^2s^2 \,, \quad B = stu\, m_Z^2$$



Differential cross sections for the process γγ → γZ versus invariant mass of outgoing photons at √s = 3 TeV. The left, middle and right panels correspond to λ_e= 0.8, -0.8, 0. Solid curves (from top downwards): (g_1 = 10^{-13} GeV^{-4}, g_2 = 0), SM.



$|\eta| < 2.5$
$m_{\gamma Z} > 1$ TeV

95% C.L. exclusion region for anomalous couplings g_1, g_2 for unpolarized $\gamma\gamma \rightarrow \gamma Z$ 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}. Couplings g_1, g_2 are in GeV^{-4}.

(S.Inan & A.K., JHEP, 10, 121, 2021)

Partial-wave expansion of helicity amplitude

(M.Jacob & G. Wick, Ann. Phys. 7, 404, 1959; ibid 281, 774 2000)

$$M_{\lambda_1\lambda_2\lambda_3\lambda_4}(s,\theta,\varphi) = 16\pi \sum_J (2J+1)\sqrt{(1+\delta_{\lambda_1\lambda_2})(1+\delta_{\lambda_3\lambda_4})} \times e^{i(\lambda-\mu)\phi}\, d^J_{\lambda\mu}(\theta)\, T^J_{\lambda_1\lambda_2\lambda_3\lambda_4}(s)$$

$d^J_{\lambda\mu}$ = Wigner's (small) d-function

$$T^J_{\lambda_1\lambda_2\lambda_3\lambda_4}(s) = \frac{1}{32\pi}\frac{1}{\sqrt{(1+\delta_{\lambda_1\lambda_2})(1+\delta_{\lambda_3\lambda_4})}}\int_{-1}^{1} M_{\lambda_1\lambda_2\lambda_3\lambda_4}(s,z)\, d^J_{\lambda\mu}(z)\, dz$$

Partial-wave unitarity bound

$$\left|T^J_{\lambda_1\lambda_2\lambda_3\lambda_4}(s)\right| \leq 1$$

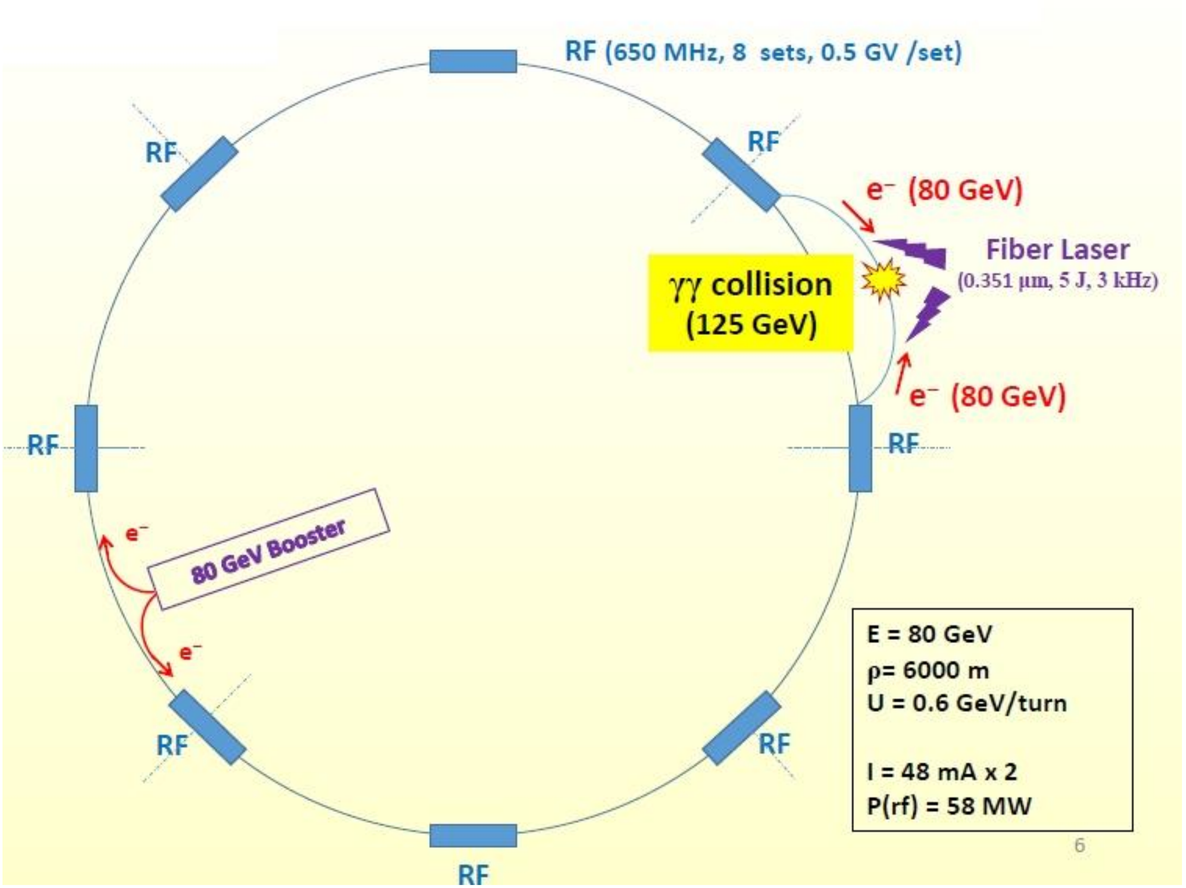
Invisible dark photons

Diagonalization of gauge fields W^3, B and DP field A'

$$\begin{pmatrix} W_\mu^3 \\ B_\mu \\ \bar{A}'_\mu \end{pmatrix} = \begin{pmatrix} c_W & s_W & -s_W\varepsilon \\ -s_W & c_W & -c_W\varepsilon \\ t_W\varepsilon & 0 & 1 \end{pmatrix} \begin{pmatrix} Z_\mu \\ A_\mu \\ A'_\mu \end{pmatrix}$$

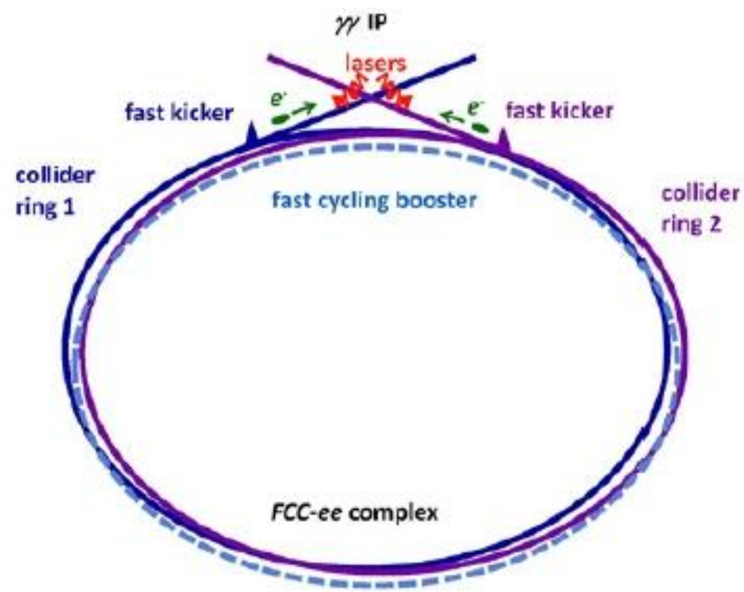
CEPC as a γγ factory

(Ch. Zhang & W. Chou, Photon Beam Workshop, Padova, Italy, 2017)



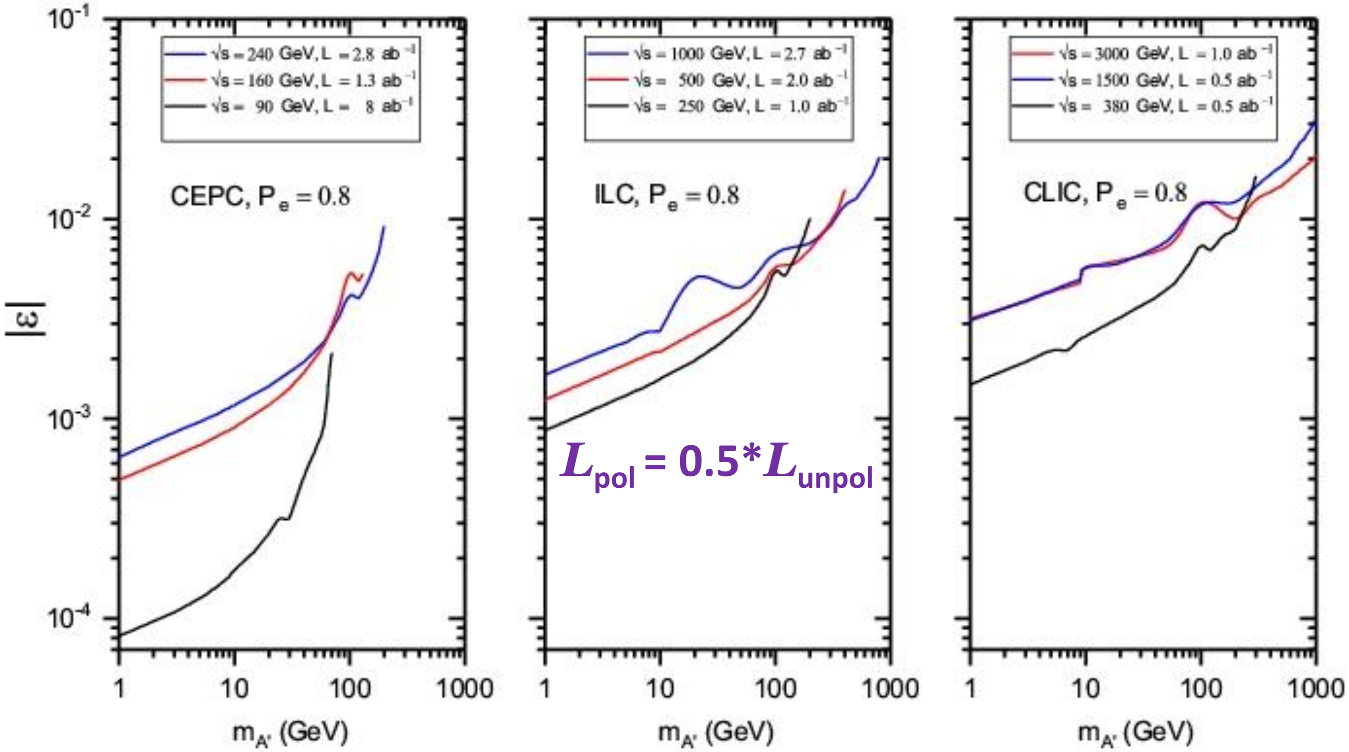
FCC-ee as a γγ factory

(R. Alesan et al., IPAC 2015, Richmond, VA, USA, 2015)



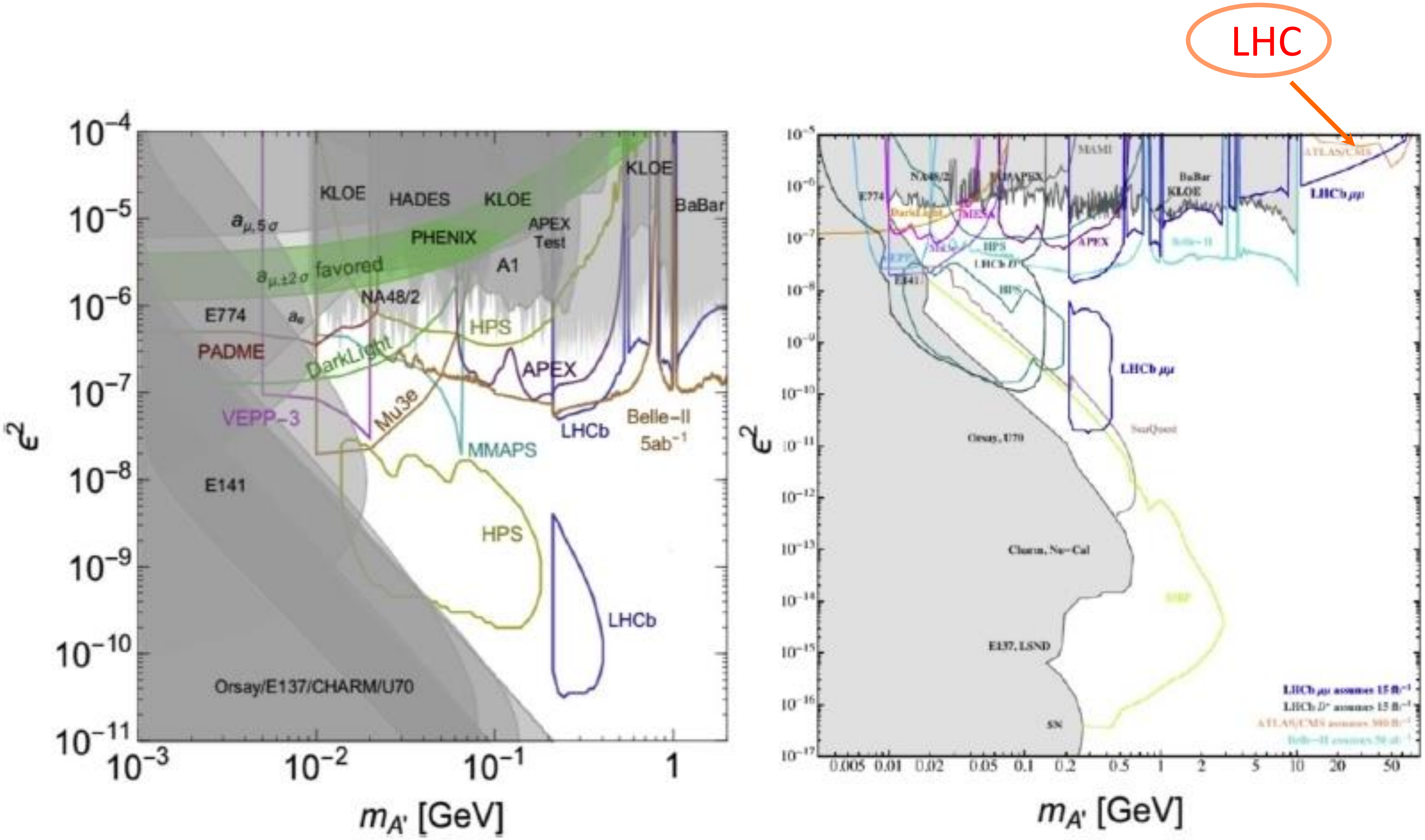
γγ Higgs factory can be realized by back-scattering two counter-propagating electron bunches off laser pulses

(S.Inan & A.K., EPJC, 82, 592, 2022)



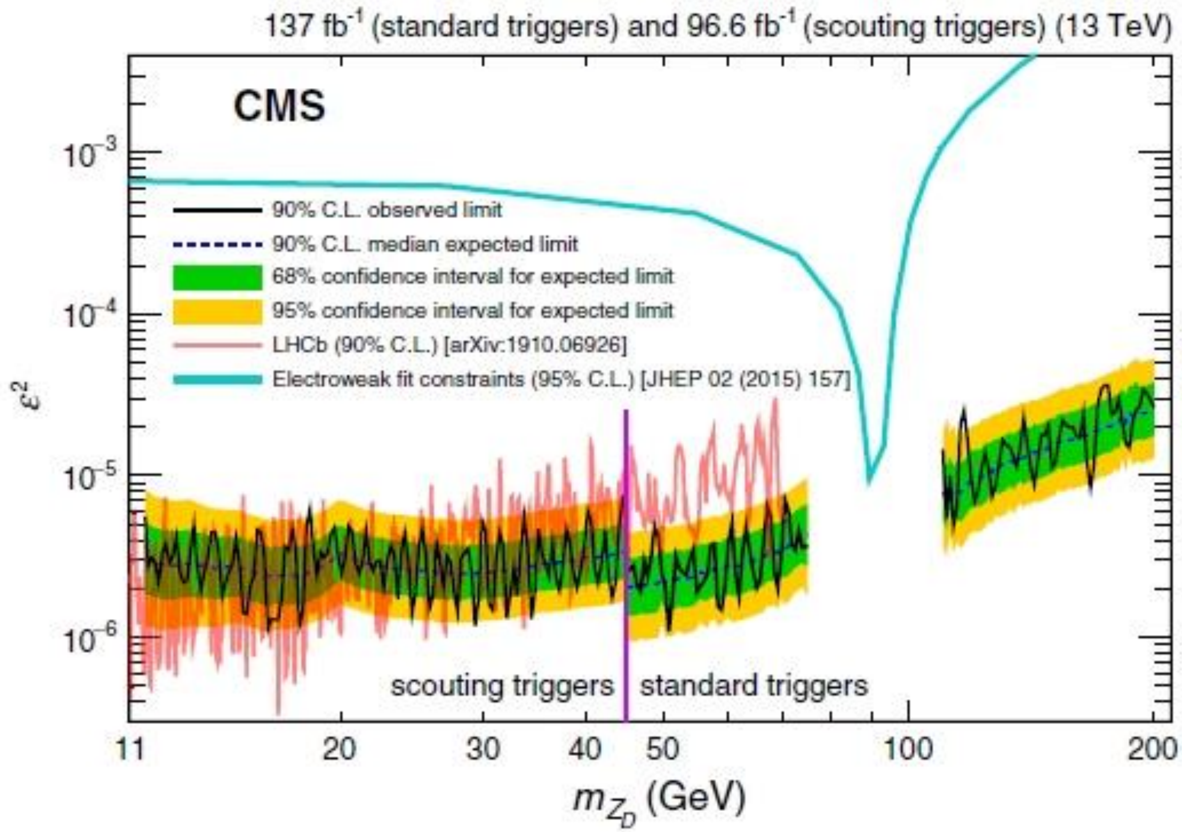
Excluded bounds at 95% C.L. on DP mass $m_{A'}$ and mixing parameter ε for invisible DP production in collision of *unpolarized* photon and electron whose *polarization is* 80%

$p_{e,t} > 10$ GeV, $|\eta_e| < 2.5$, $|m_{A'} - m_{inv}| < 10$ GeV



Existing bounds (shaded regions) for DP in visible decays

(A. Filippi & M. De Napoli, Rev. Phys. 5, 100042, 2020)



CMS limit on mixing parameter for DP decaying into muon pair

(CMS Collab., Phys. Rev. Lett. 124, 131802, 2020)

DP at future ep colliders LHeC and FCC-he

(CMS Collab., Phys. Rev. D 101, 015020, 2020)