Exploring Dark Sectors at FCC

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Motivations

- So far, physics beyond SM assumed to interact with SM via gauge interactions
  → susy, compositness, technicolor, extra-dimensions…

- No signals of TeV New Physics (NP) observed @ LHC. Hopes for HL-LHC ?

maybe we were just looking in the wrong direction

- accessible sector of NP could be **light** and **feebly interacting** (FI) with SM

- **not** fully explored @ LHC

- **Dark Sector:** a natural theoretical framework for physics of FI Particles

- DS might contain **Dark Matter,** but not necessarily
  → DM eluded so far all direct searches and might well be of pure gravitational origin
  missing mass: due to black holes; dynamical origin: modification of GR, MOND, etc..

- Future colliders (FCC-ee, FCC-hh, ..) → powerful tools for exploring Dark Sector

Dark Sector

- Dark Sector (DS): made by particles **neutral** under SM gauge interactions
- DS can interact with SM in two ways:

  gravitationally (no hope) or through **portals** to SM sector

- observing DS in lab experiments require existence of portals
- mediated by: **renormalizable** and **non-renormalizable** interactions
- DS particles naturally feebly coupled to SM → non-renormalizable interactions
- DS might possess rich internal structure and its own interactions
- could contain light or massless gauge bosons → dark photon (dark QED)

Portals Schemes

popular theoretical frameworks

Portal	Coupling
Vector (Dark Photon, A_μ)	$-\frac{\varepsilon}{2\cos\theta_W} F'_{\mu\nu} B^{\mu\nu}$
Scalar (Dark Higgs, S)	$(\mu S + \lambda_{HS} S^2) H^\dagger H$
Fermion (Sterile Neutrino, N)	$y_N LHN$
Pseudo-scalar (Axion, a)	$\frac{a}{f_a} F_{\mu\nu} \tilde{F}^{\mu\nu}$, $\frac{a}{f_a} G_{i,\mu\nu} \tilde{G}_i^{\mu\nu}$, $\frac{\partial_\mu a}{f_a} \overline{\psi} \gamma^\mu \gamma^5 \psi$

non-renormalizable interactions → effective couplings (require mediators) → naturally feebly (loop induced)

tree-level renormalizable interactions → dim 4,3 operators → mechanism required to justify suppression

list above not include → **massless** Dark Photon (different signatures than massive scenario and not fully explored at colliders)

non-renormalizable interactions → require mediators → naturally feebly (loop induced)

Higgs portal

DS coupled to the Higgs boson via a singlet scalar field S (Dark Higgs)

$$(\mu S + \lambda_{HS} S^2) H^\dagger H$$

SM Higgs boson

Two types of couplings

- μ after Higgs vev → Higgs-S mixing mass term → diagonalization → $\sin\theta$
  needed to induce decay (at least in SM particles)
- λ_{HS} → can generate pair (SS) production

- contribute to the invisible Higgs decay H → S S with coupling $g_{HSS} = \lambda_{HS} v^2$
- naturally satisfying the condition $\lambda_{HS} \lesssim m_S^2 / v^2$

SM Higgs vev

S mass

Motivations (Higgs portal)

– **Can generate Barion asymmetry of the Universe**

Cohen-Kaplan PLB 199 (1987)

$$\mathcal{L}_B = \frac{1}{\Lambda} \partial_\mu \phi J_B^\mu$$

barion current

- if there are baryon violating interactions in thermal equilibrium barions and anti-baryons will equilibrate with different thermal distributions

– **can also address the Higgs-fine tuning problem via *relaxation* mechanism**

Graham-Kaplan-Rajendran PRL 115 (2015)
Frugiuele-Fuchs-Perez-Schlaffer JHEP 10 (2018)

- Dynamical evolution during the early universe drives the Higgs mass to a value much smaller than the cutoff

- requires inflation sector + ϕ having effective axion-like couplings to QCD gluons)

– can play role of mediator between SM particles and light DM

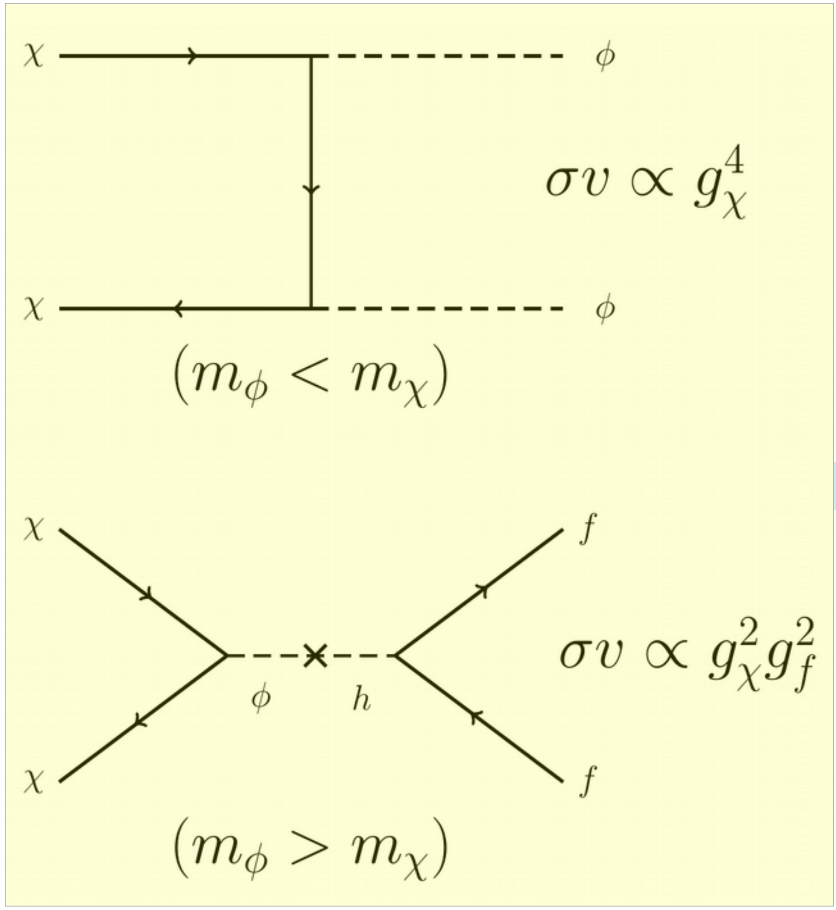
Burges-Pospelov-Veldhuis, NPB 619 (2001)
Pospelov-Ritz PRD 84 (2011)

$\phi \quad h$ → mass eigenstates

Assume ϕ couples to light DM χ → Dirac fermion, SM singlet

$$\mathcal{L}_{\phi,\mathrm{DM}} = \phi(g_\chi \bar{\chi}\chi + g'_\chi \bar{\chi}\gamma^5\chi)$$

ϕ acquires couplings to SM fermions due to Higgs-mixing and Higgs-Yukawa coupling to fermions

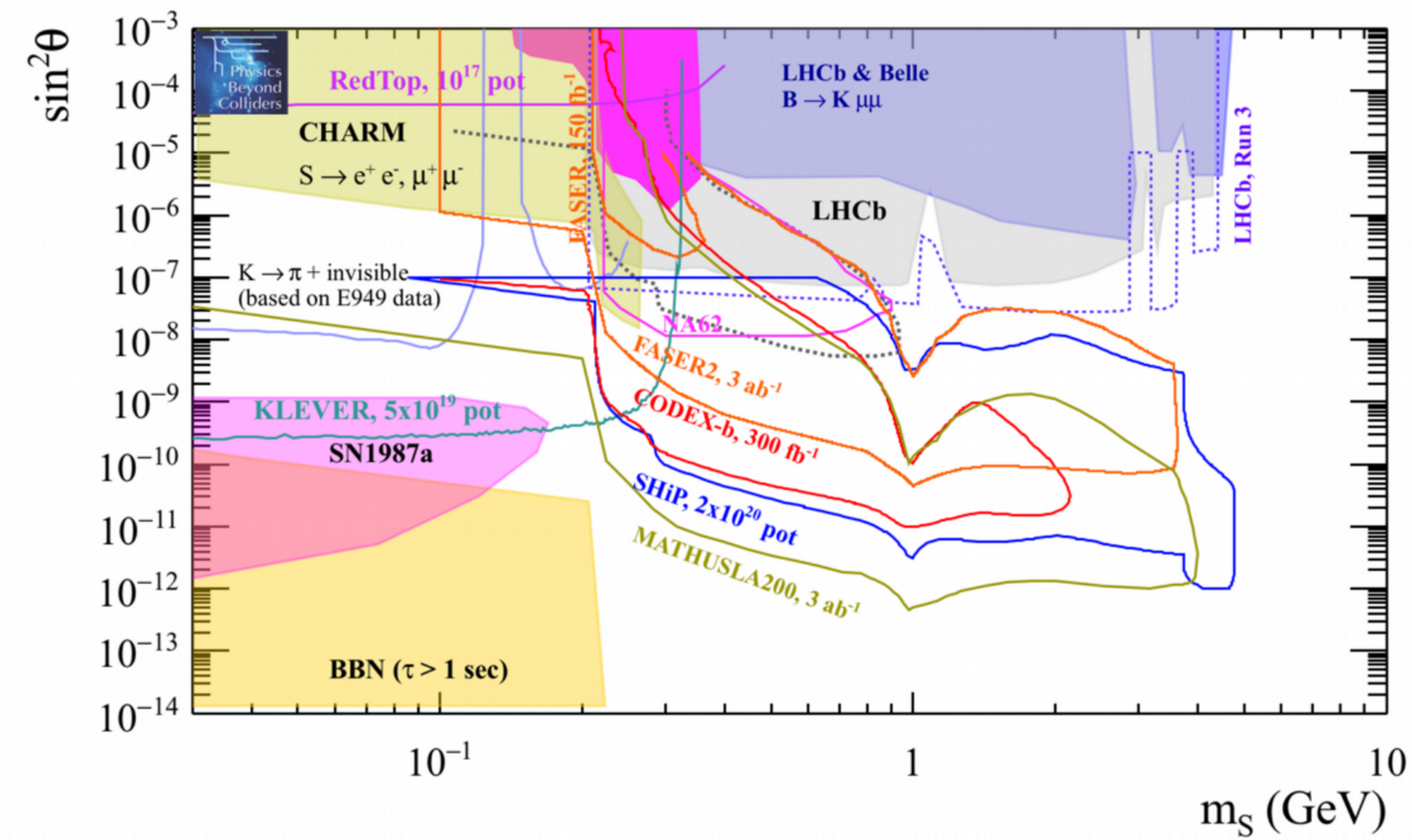


$$\mathcal{L}_{\phi,\mathrm{SM}} = \phi \sin\theta \sum_f \frac{m_f}{v} \bar{f} f \qquad g_f \equiv \frac{m_f}{v} \sin\theta$$

Giving rise to χ annihilation in the early universe

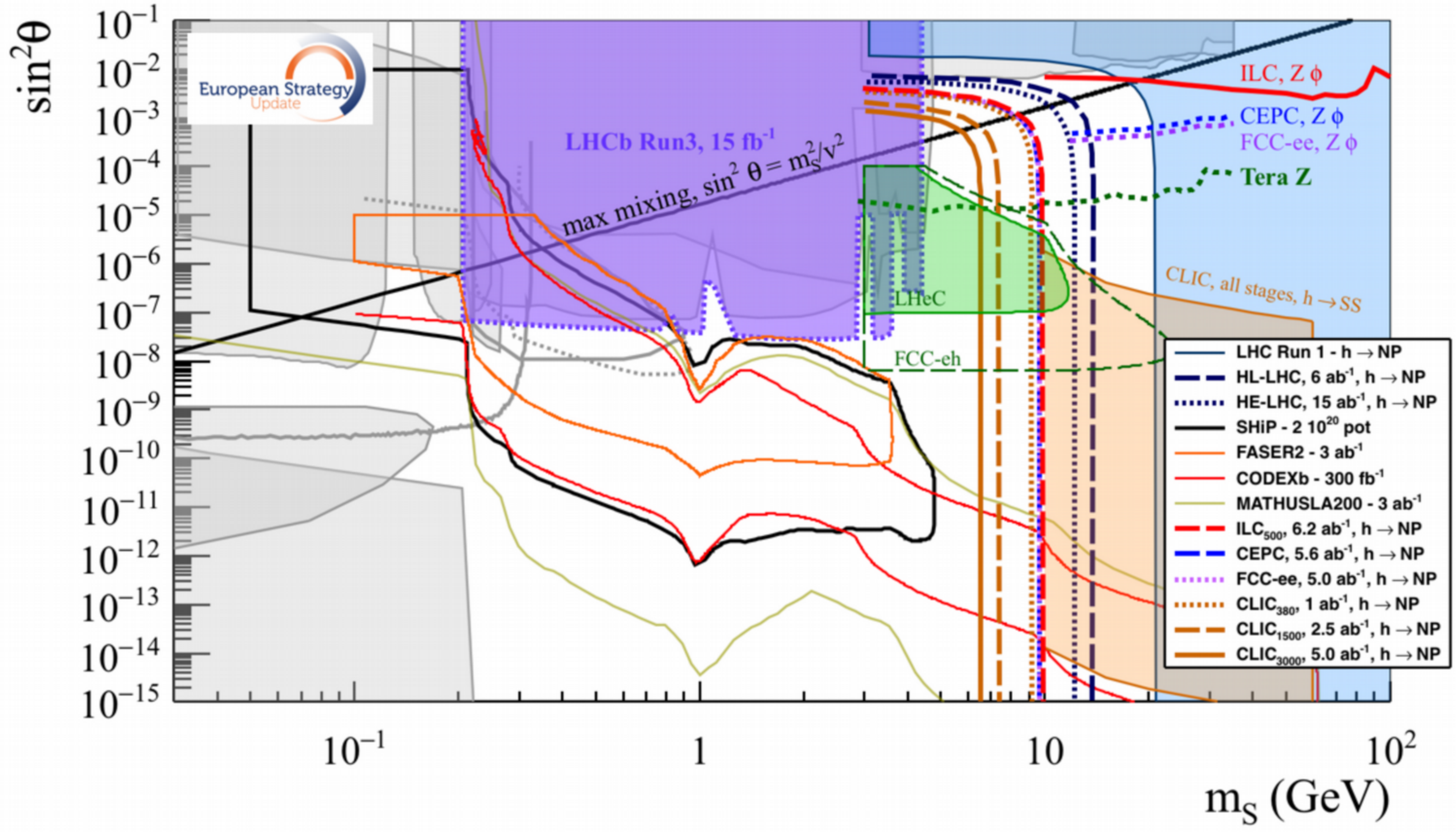
IF $m_\phi > 2m_\chi$ $\quad \phi$ mainly decay into DM

Higgs portal (m_S < 10 GeV)



FASER2, CODEX-b, MATHUSLA-200 → future experiments/detectors searching for LLP @ LHC-HL

- **low range mass < 10 GeV:** optimally covered by **SHiP** at beam dumb facility and **MATHUSLA200**
- **masses above few GeV:** **FASER2** with 3ab^{-1} will explore these regions compatible with **CODEX-b;** also explored by **CLIC** and **LHC-eC/FCC-eh** via displaced vertex technique
- NA62^{++} and FASER projects prospects in 5y, others in 10-15 y



Higgs portal

(summary)

- **Shaded grey areas:** already excluded
- **Vertical lines** correspond to the bounds on untagged Higgs decay $\Gamma_h^{\mathrm{NP}} = \Gamma_h^{\mathrm{unt}} = \Gamma(h \to \phi\phi)$
- **Large mass and couplings regime:** covered by e^+e^- colliders

not necessarily undetectable
Frugiuele-et al JHEP 10 (2018)

(FCC-ee, CLIC, ILC, CEPC, Tera Z) using recoil technique $e^+e^- \to ZS$ or running at Z pole via $e^+e^- \to Z \to S\ell^+\ell^-$

Heavy Neutral Leptons (N) portal

$$y_N LHN$$

motivations

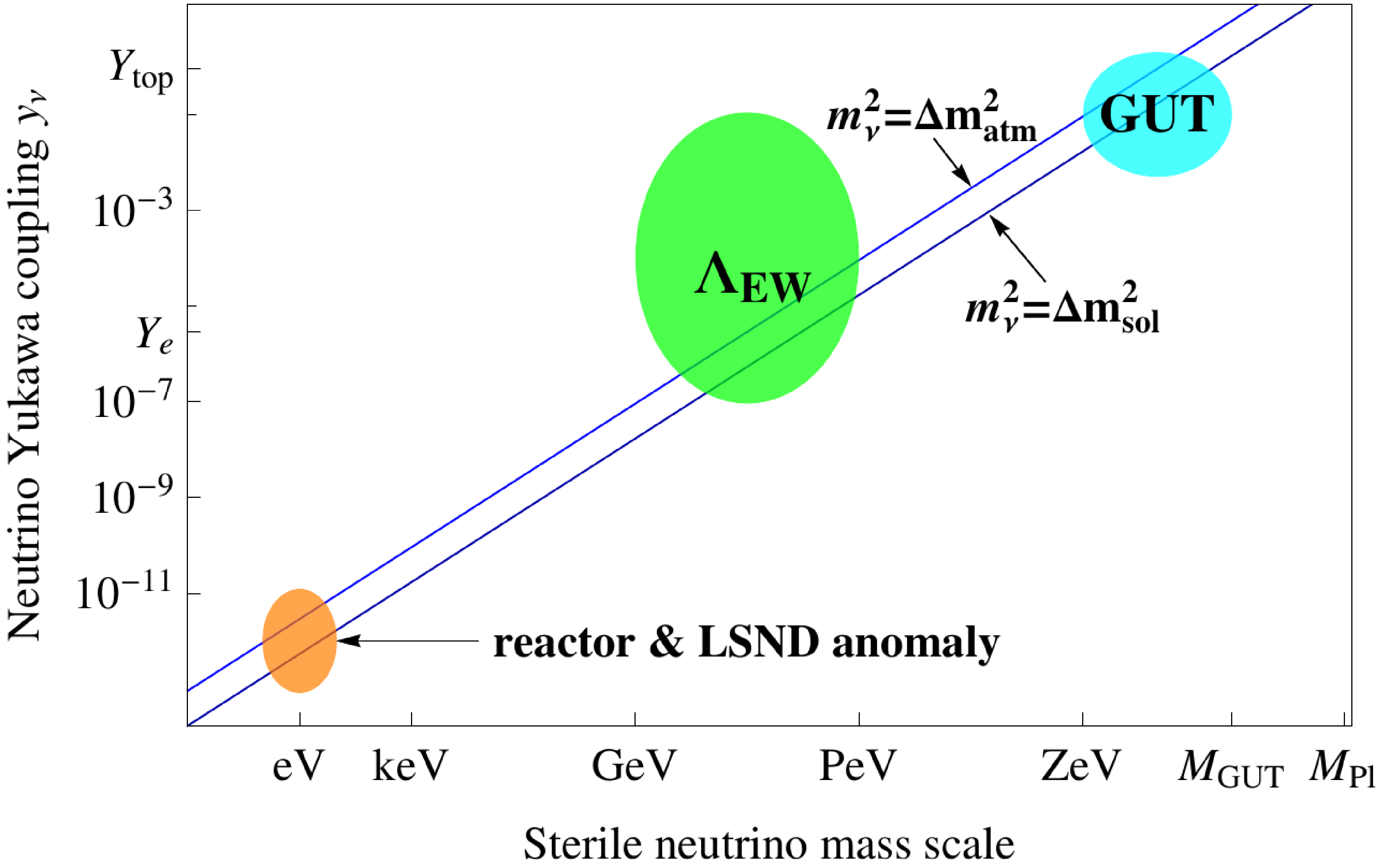
- Can explain light neutrino flavor oscillation via Type-I see-saw mechanism
- require existence of right-handed neutrinos ν_R
- couplings with ν_R generically violate CP → potentially generating matter-anti-matter asymmetry in primordial plasma
- **Leptogenesis:** above T(sphaleron) > 130 GeV asymmetry converted into net barion number → most promising explanation for barion-antibarion asymmetry in universe

D'Onofrio-Rummukainen-Tranberg PLB 155 ('85)
Akhmedov-Rubakov-Smirnov PRL 81 ('98)

- Studied in connection with : Large-scale structure formation, BBN, cosmic wave background, diffuse extra-galactic background radiation, supernovae, etc..

Viel et al. PRD 71 (2005)
Ruchayskiy-Ivashko JCAP 1210 (2012)
Drewes, IJMP E22 (2013)

Landscape of neutrino sterile extensions BSM



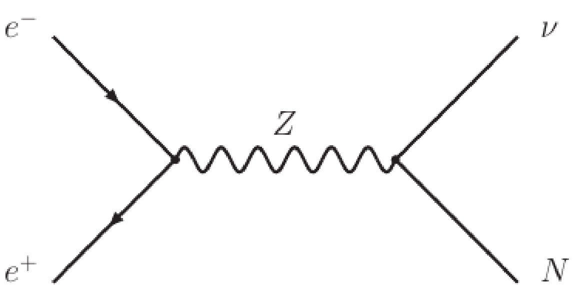
green area → – EW scale neutrino models with protective lepton number like symmetry.
– masses relevant range for particle colliders experiments .

blue area → naive expectations

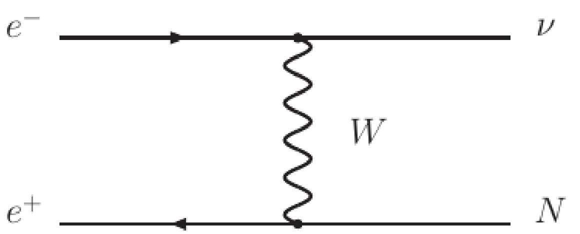
heavy sterile neutrinos

(courtesy of B.Mele)

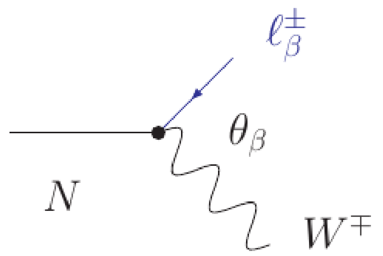
- Symmetry-protected seesaw allows for EW-scale M_{nu} and o(1) mixing
- mix with active nu's by $\theta_\alpha = y_{\nu_\alpha} \frac{v}{\sqrt{2}M}$
- presently $|\theta|^2 \leq 10^{-3}$

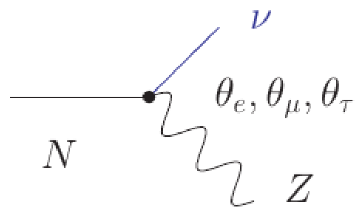


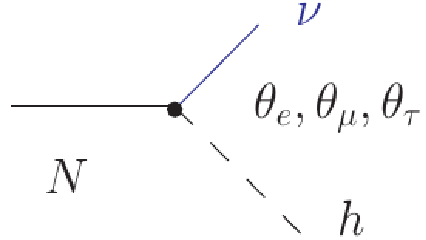
production channel: $\mathbf{Z_s}$

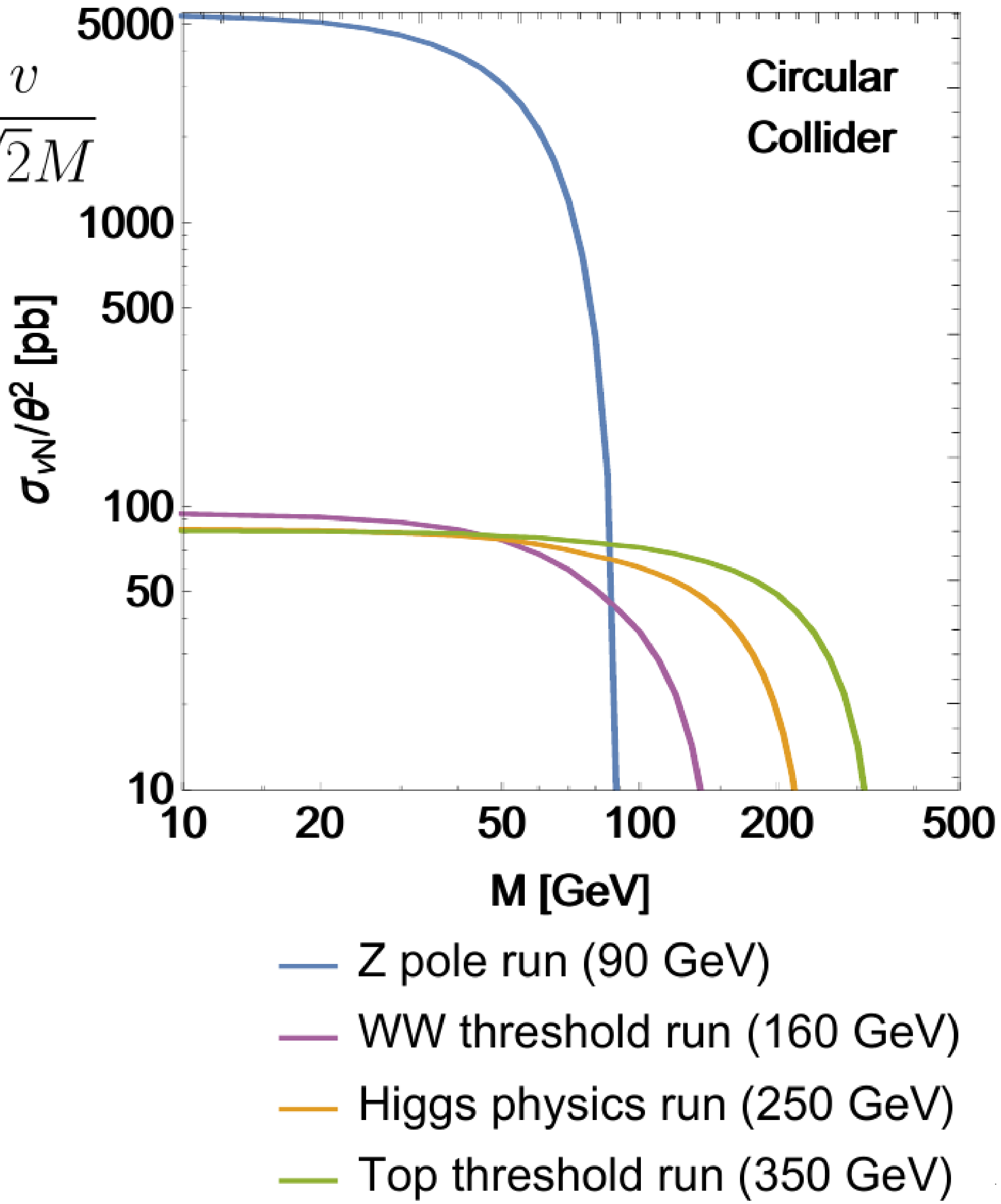


production channel: $\mathbf{W_t}$





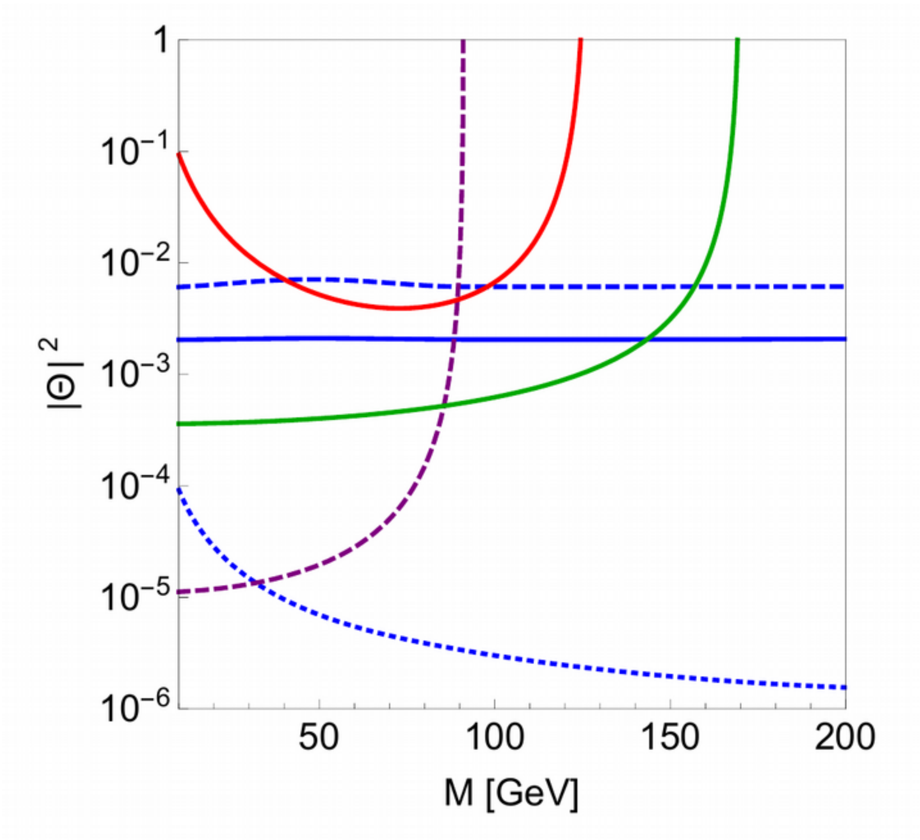


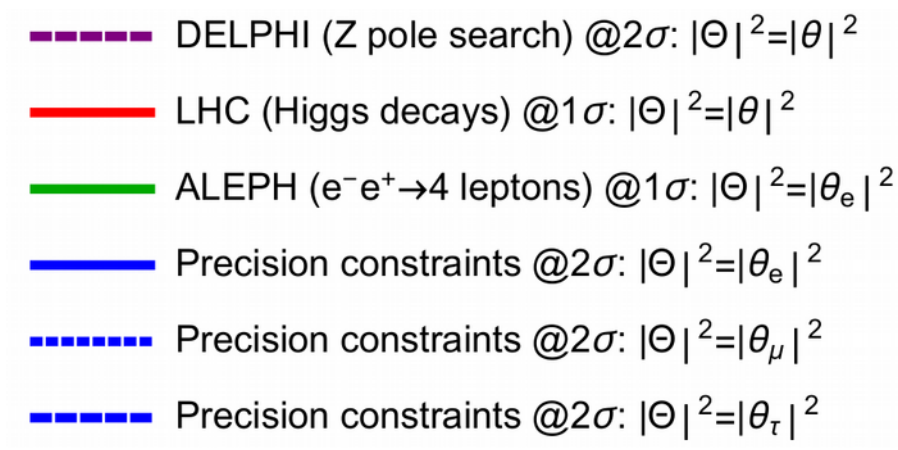


Antusch, Cazzato, Fischer
1612.02728

indirect constraints

Antush-Cazzato-Fisher
[arXiv:1612.02728]



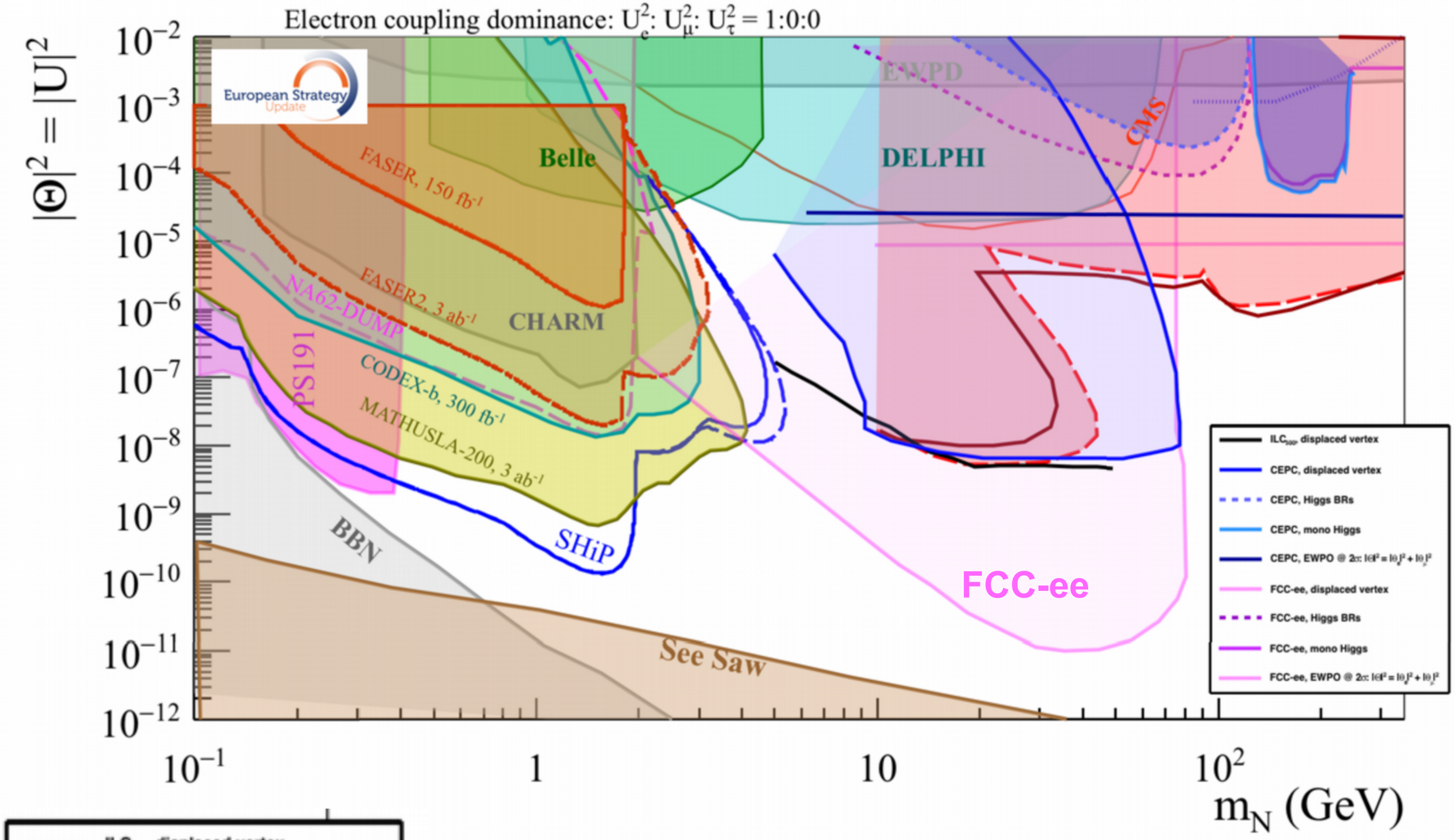


- Precision constraints from muon decays

$$\sigma_{\mu^-\to e^-\nu\bar{\nu}} = \left(\mathcal{N}\mathcal{N}^\dagger\right)_{ee}\left(\mathcal{N}\mathcal{N}^\dagger\right)_{\mu\mu} \cdot \sigma^{\mathrm{SM}}_{\mu^-\to e^-\nu\bar{\nu}}$$

$$G_F^2 \;\to\; G_\mu^2 = G_F^2 \cdot (\mathcal{N}\mathcal{N}^\dagger)_{ee}(\mathcal{N}\mathcal{N}^\dagger)_{\mu\mu}$$

- Lepton universality
- Rare LFV decays
- CKM unitarity tests



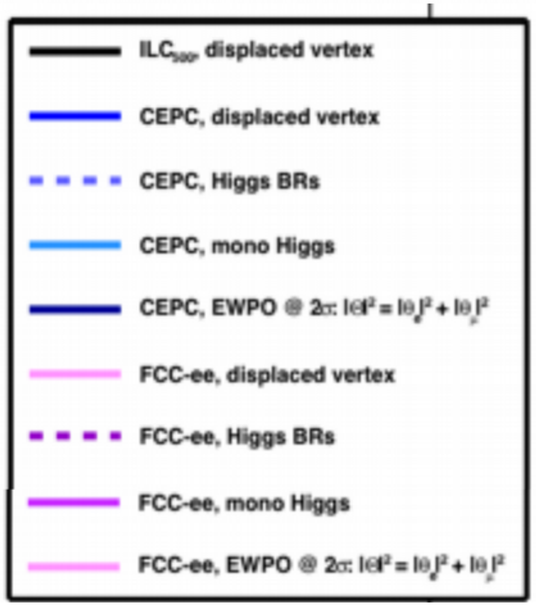
- from H invisible width affecting BRs

$$\Gamma(h \rightarrow \nu N)$$

- From Z invisible width

$$Br(Z \rightarrow \nu\, N) < 1.3 \times 10^{-6}$$

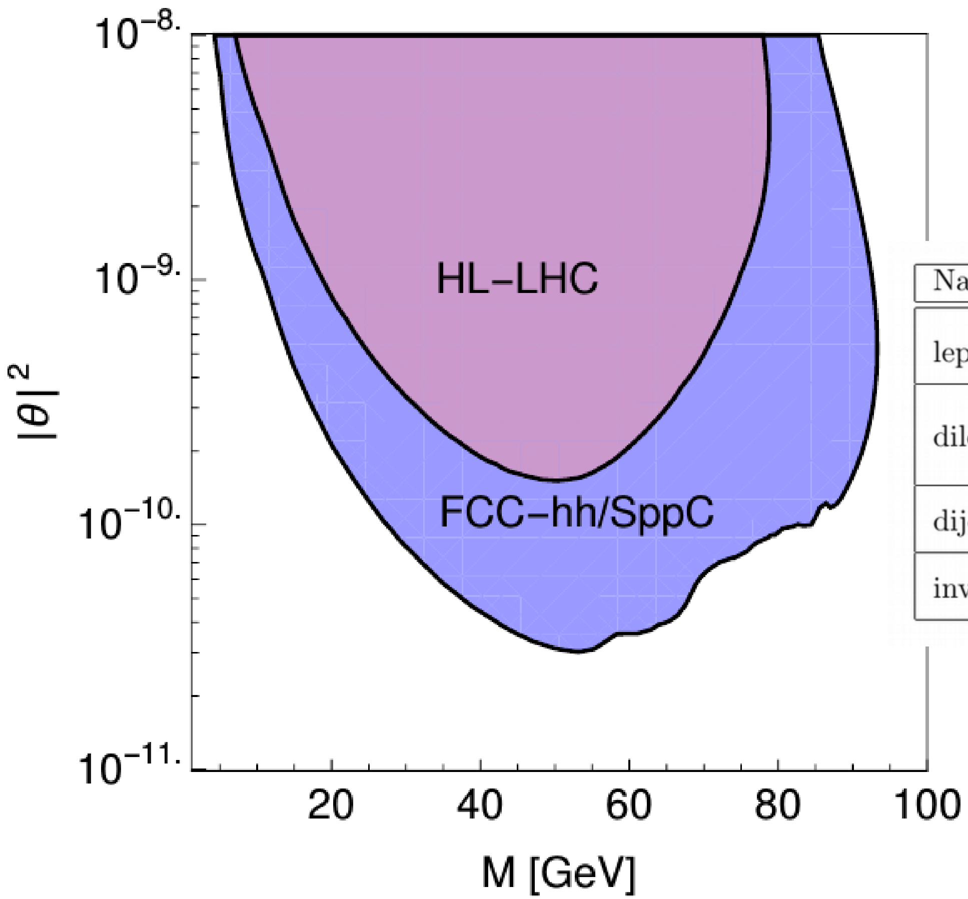
- from mono-Higgs
  If $M_N > m_H$
  $N \rightarrow h\ \nu$
  $\tau+\tau-$



- **Low mass range < 5 GeV:** dominated by SHiP, followed by experiments at LHC, MATHUSLA-200, FASER, CODEXb
- **Intermediate masses 5-90 GeV:** explored by ILC, CEPC, and FCC-ee (displaced vertex searches) dominated by FCC-ee at Z pole (10^{12} Z)
- **High masses above 90 GeV:** explored using mono-Higgs, mono-Z signatures
- SHiP and FCC-ee at Z-pole have potential to exclude regions and couplings compatible with leptogenesis almost down to the see-saw limit

From displaced vertex searches at hadron colliders

Antush-Cazzato-Fisher
[arXiv:1612.02728]



Name	Final State	Channel [production,decay]	$\lvert\theta_\alpha\rvert$ dependency
lepton-dijet	$\ell_\alpha \nu j j$	$[\mathbf{W_t}, W]$, $[\mathbf{Z_s}, W]$	$\frac{\lvert\theta_e\theta_\alpha\rvert^2}{\theta^2}^{(**)}, \lvert\theta_\alpha\rvert^{2\,(**)}$
dilepton	$\ell_\alpha \ell_\beta \nu\nu$	$[\mathbf{W_t}, \{W, Z(h)\}]$, $[\mathbf{Z_s}, \{W, Z(h)\}]$	$\left\{\frac{\lvert\theta_e\theta_\alpha\rvert^2}{\theta^2}^{(*)}, \lvert\theta_e\rvert^{2\,(*)}\right\}^{(**)}, \left\{\lvert\theta_\alpha\rvert^{2\,(*)}, \lvert\theta\rvert^2\right\}^{(**)}$
dijet	$\nu\nu j j$	$[\mathbf{W_t}, Z(h)]$, $[\mathbf{Z_s}, Z(h)]$	$\lvert\theta_e\rvert^{2\,(**)}, \lvert\theta\rvert^{2\,(**)}$
invisible	$\nu\nu\nu\nu$	$[\mathbf{W_t}, Z]$, $[\mathbf{Z_s}, Z]$	$\lvert\theta_e\rvert^{2\,(**)}, \lvert\theta\rvert^{2\,(**)}$

- For M > 200 GeV better sensitivities are given by LFV dilepton-dijets final states $\ell_\alpha \ell_\beta j j$ for $\alpha \neq \beta$
- that can test combinations of angles $|\theta_e\theta_\mu|^2/\theta^2$, $|\theta_e\theta_\tau|^2/\theta^2$
- LHC run2 already sensitive to 10^{-3} angle combinations to this channel

Pseudo-scalar (ALP) portal

$$\mathcal{L}_a = g_{a\gamma\gamma}\left(F_{\mu\nu}\tilde{F}^{\mu\nu}\right) + \frac{\partial_\mu a}{f_a}\left(\bar{\psi}\gamma^\mu\gamma^5\psi\right)$$ → chirally suppressed

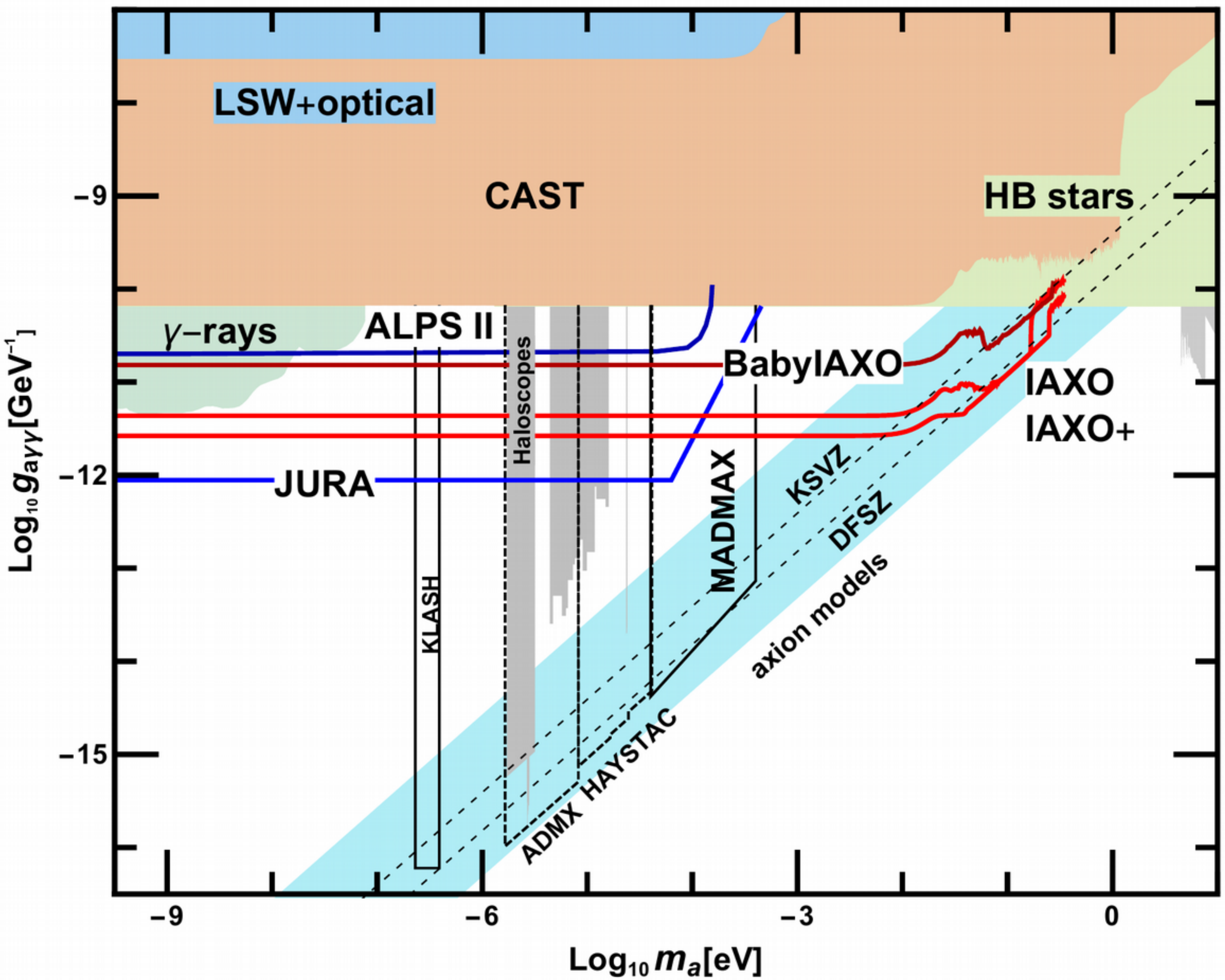
- QCD axions predicted by Peccei-Quinn mechanism to solve the CP problem of strong interactions
- QCD axion models restricted to sub-eV mass range
- Terrestrial experiments and astrophysical observation restrict QCD axions $g_{a\gamma\gamma} \lesssim 10^{-10}\,\mathrm{GeV}^{-1}$
- For masses below eV and $g_{a\gamma\gamma} \lesssim 10^{-10}\,\mathrm{GeV}^{-1}$ are stable on cosmological scale → DM candidate!
- Less constrained are generalization to **axion-like particles (ALP)** of different mass
- ALP can act as mediators between light DM and SM particles

typical production mechanisms

- **Beam dumb experiments:** Primakoff effect → via axion-photon conversion in external magnetic field and $\pi^0/\eta^0 \to \gamma\, a$ via pion/eta-axion kinetic mixing → $\varepsilon\partial_\mu a\partial^\mu\pi^0$
- **hadron-colliders → DY** via $Z \to a\gamma$
- **Lepton-colliders** $e^+e^- \to (Z) \to a\gamma$

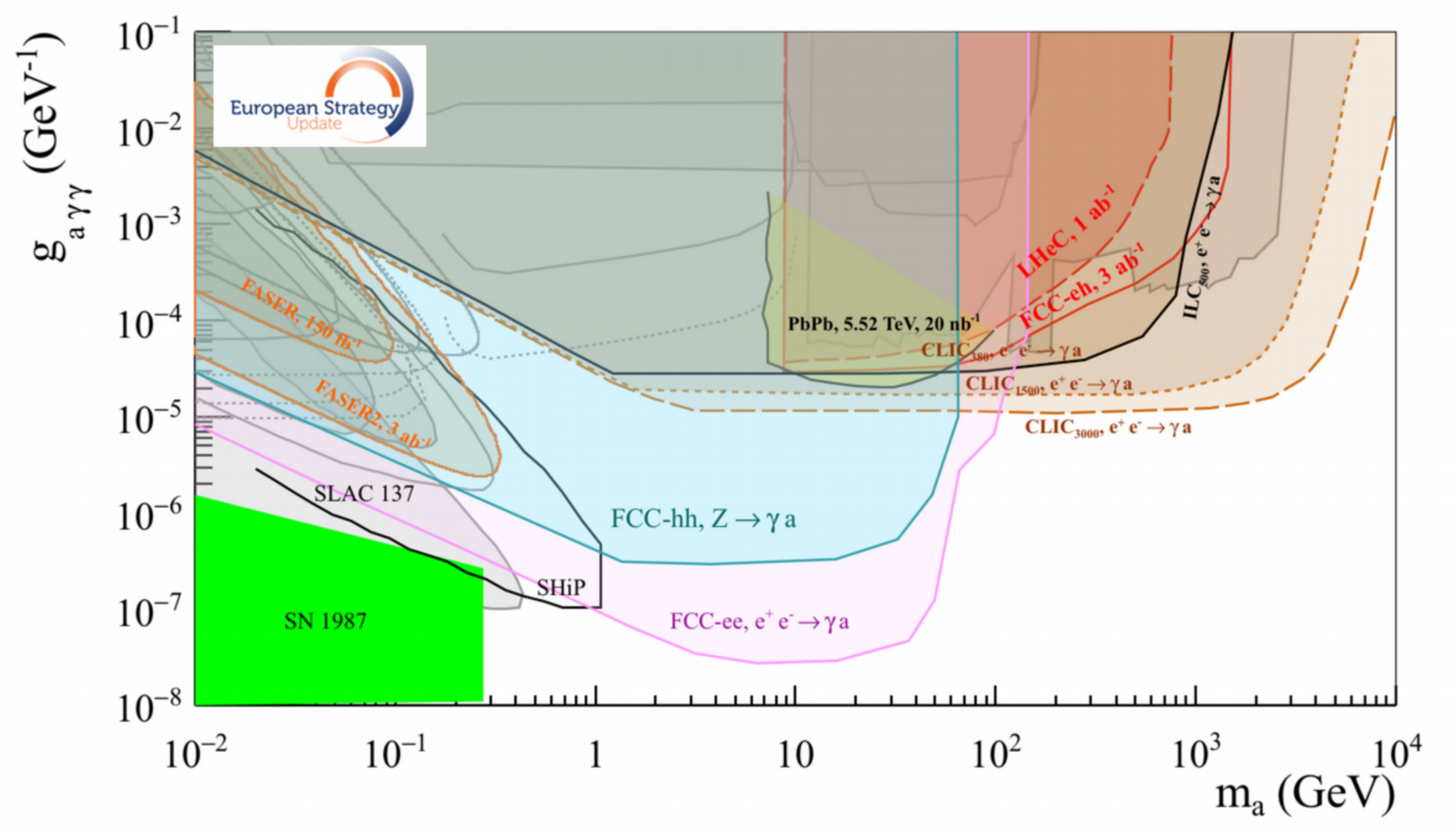
with $a \to \gamma\gamma$ **or** axion stable detected as missing energy

Exclusion regions axions below eV scale



astrophysical limits → green
pure lab experiments → blue
helioscopes → red
haloscopes → grey

} → Primakoff



$$1\ \mathrm{GeV} < m_a < 90\ \mathrm{GeV}$$

optimally explored by e+e- colliders CEPC, CLIC, ILC, **FCC-ee** and hadron colliders **FCC-hh** via Z decays

$$90\ \mathrm{GeV} < m_a < \mathcal{O}(\mathrm{TeV})$$

optimally explored by e+e- colliders CLIC,ILC, **FCC-ee** and e-p colliders **LheC** and **FCC-eh**

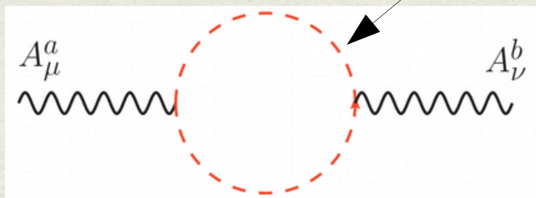
Dark Photon scenario

the vector portal

$$U(1)_a \times U(1)_b$$

$$\mathcal{L}_0 = -\frac{1}{4}F_{a\mu\nu}F_a^{\mu\nu} - \frac{1}{4}F_{b\mu\nu}F_b^{\mu\nu} - \frac{\varepsilon}{2}F_{a\mu\nu}F_b^{\mu\nu}$$

kinetic mixing always induced by renormalization effects, if messenger fields are present



no direct interaction with visible sector

J’ → Dark current
A’ → dark-photon

J → SM current
A → photon

massless

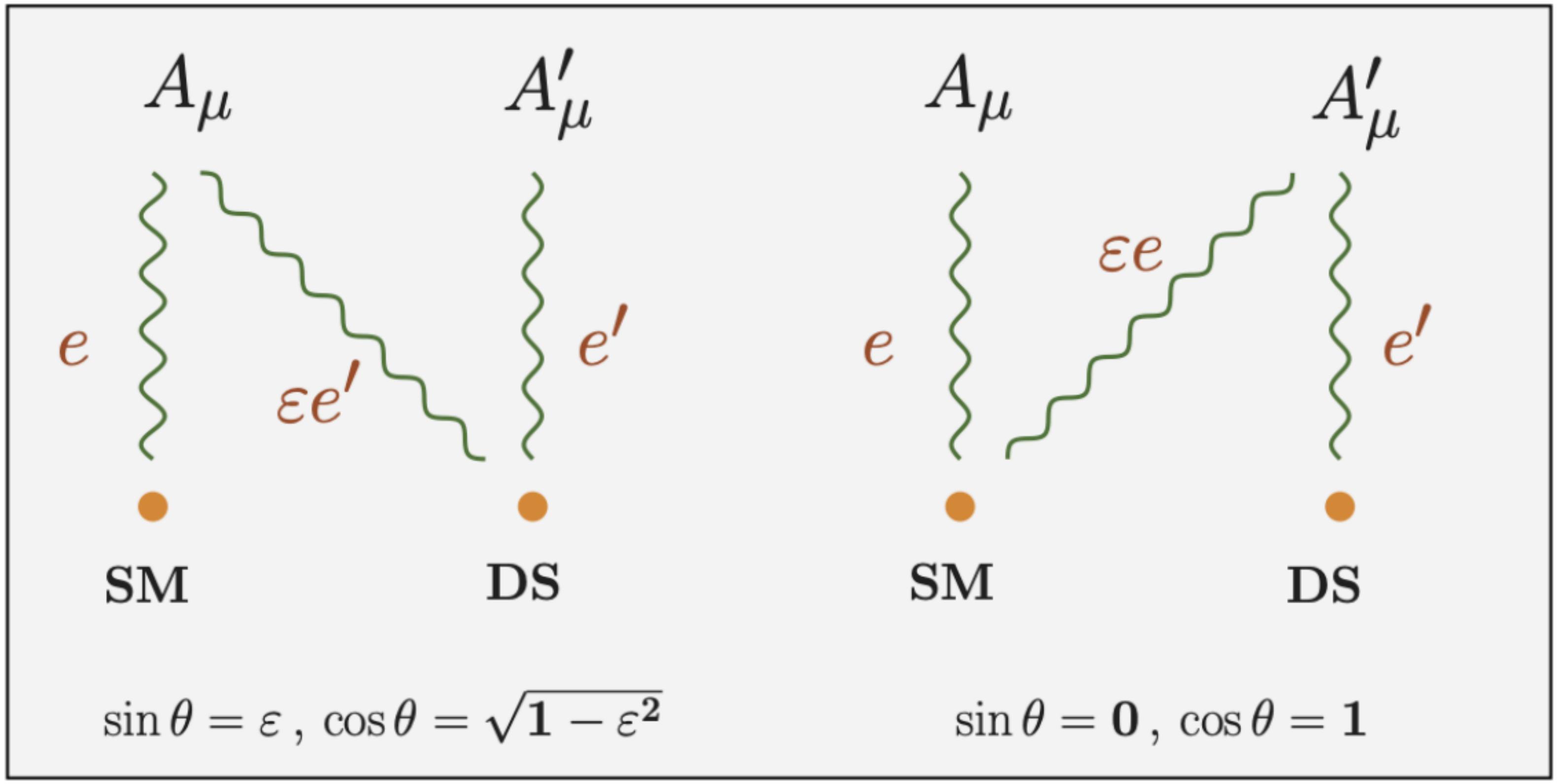
$$\mathcal{L}' = e' J'_\mu A'^\mu + \left[-\frac{e'\varepsilon}{\sqrt{1-\varepsilon^2}} J'_\mu + \frac{e}{\sqrt{1-\varepsilon^2}} J_\mu \right] A^\mu$$

$$\mathcal{L} \supset -\frac{e\varepsilon}{\sqrt{1-\varepsilon^2}} J_\mu A'^\mu \simeq -e\,\varepsilon\, J_\mu A'^\mu$$

massive

courtesy of M. Fabbrichesi

- B. Holdom, PLB 166B, 196 (1986)
- B.A. Dobreascu, PRL 94 151802 (2005); [hep-ph/0411004]
- M. Fabbrichesi, EG, G. Lanfranchi, “The physics of the Dark photon” SpringerBriefs in Physics 2020, [arXiv:2005.01515]



Massless Dark-Photon

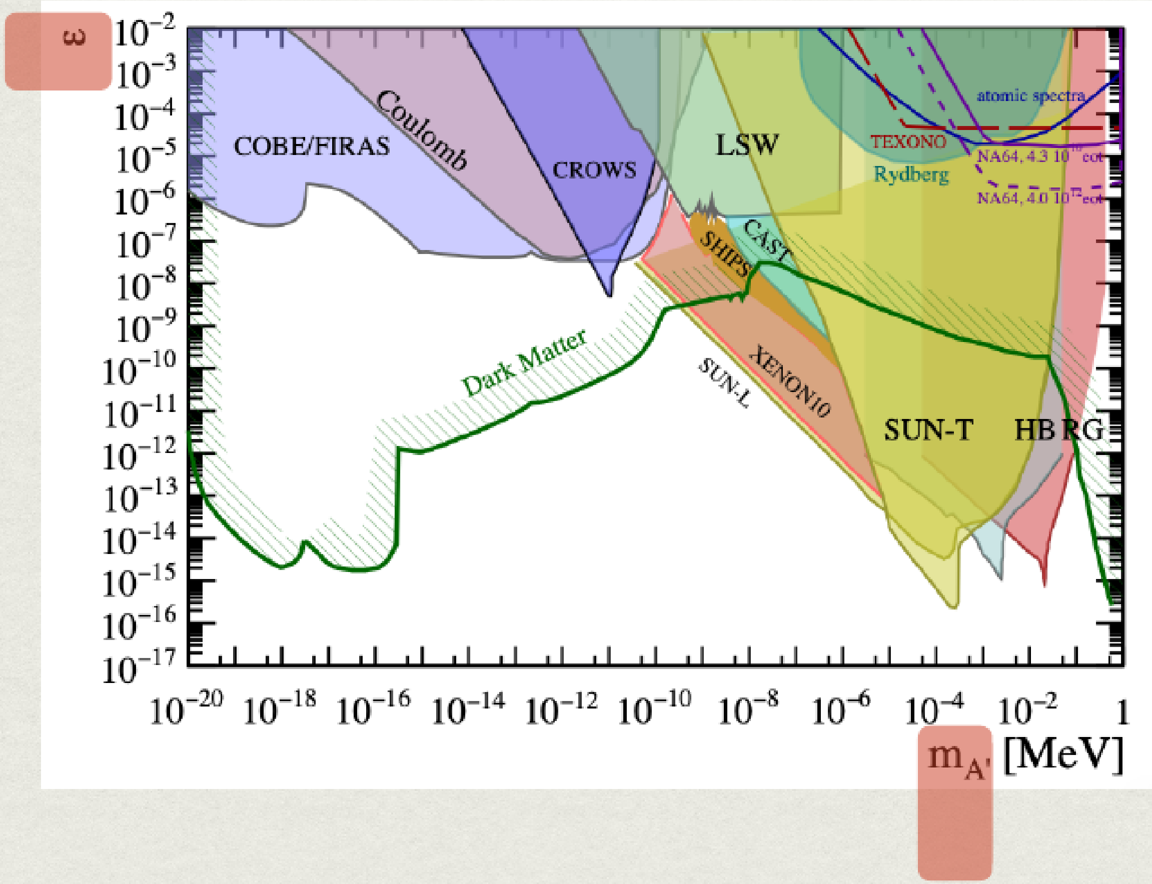
less explored scenario

Massive Dark-Photon

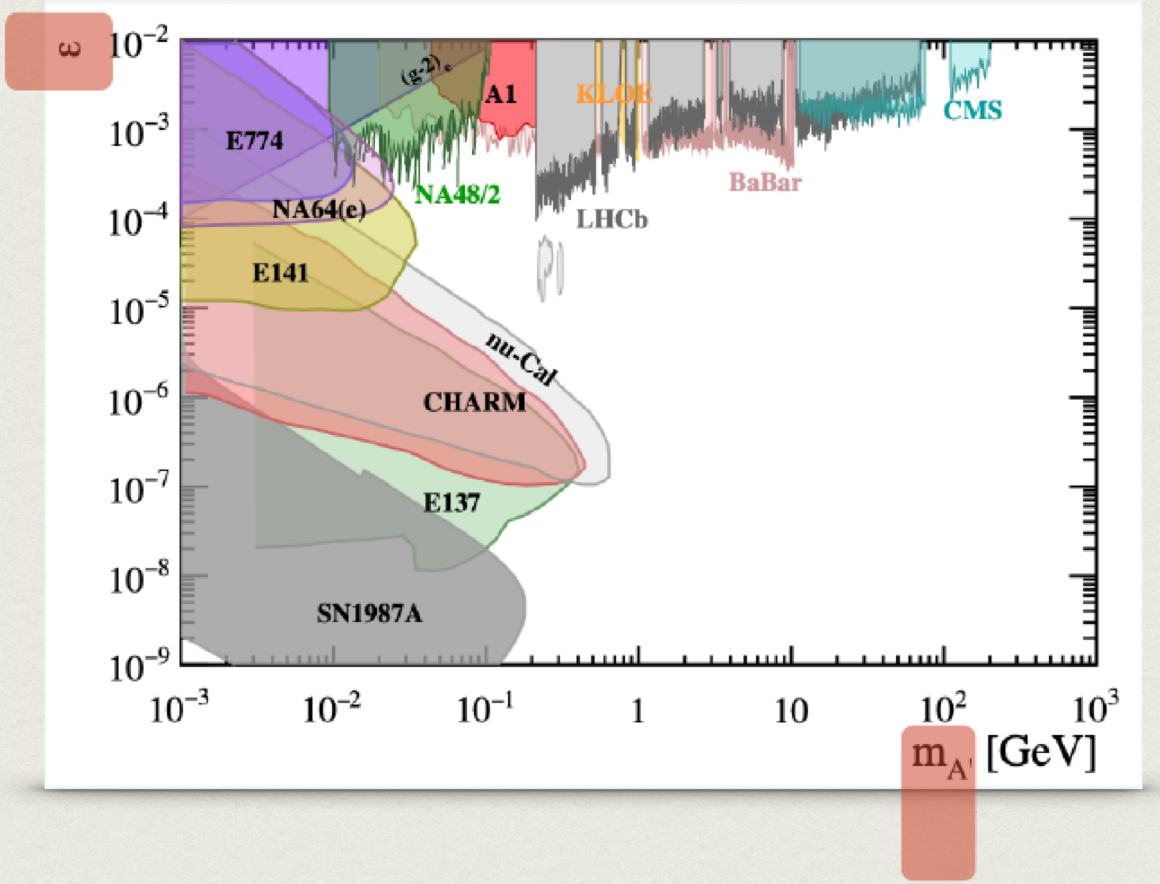
most of experimental searches focus on massive DP scenario

massive dark photon

invisible

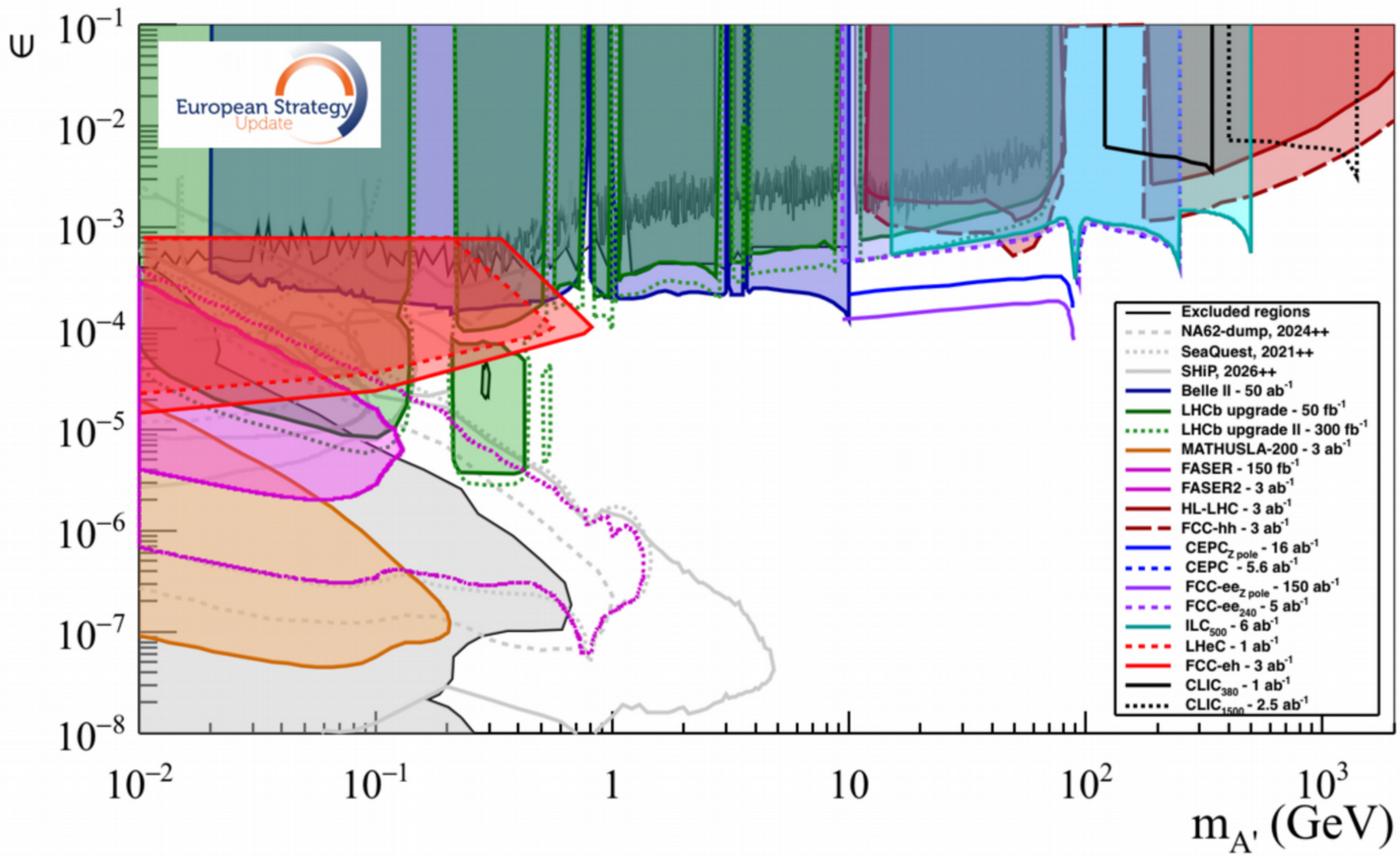


visible



limits on massive dark photon [from arXiv:2005.01515]

Massive dark photon



HL-LHC, CEPC, FCC-ee, FCC-hh curves →limits 95% C.L. , others → limits 90% C.L.

sensitivity of future colliders:

- mainly covers large-masses and large-couplings range
- fully complementary to low-mass, low-coupling regime where beam-dump and fixed target experiments are more sensitive

massless dark photon

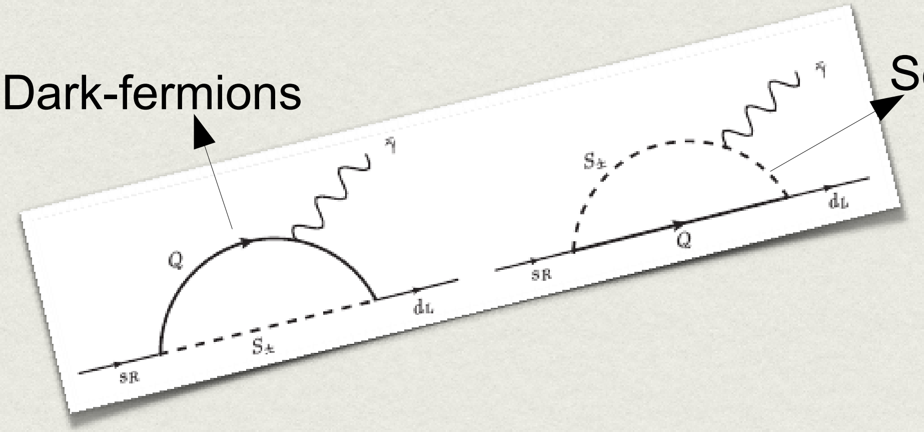
the **massless** dark photon is not
the massless limit of the **massive** dark photon

no tree-level couplings with SM fermions (can be rotated away)

we need a specific benchmark

Dark-fermions

Scalar-messengers



$d_M^{ij} \equiv |\mathbb{D}_M^{ij}|$

$$\boxed{\mathcal{L} = \frac{e_D}{2\Lambda^2}\overline{\psi}_L^i\,\sigma_{\mu\nu}\left(\mathbb{D}_M^{ij} + i\gamma_5\,\mathbb{D}_E^{ij}\right) H\psi_R^j\,F'^{\mu\nu} + \text{H.c.}}$$

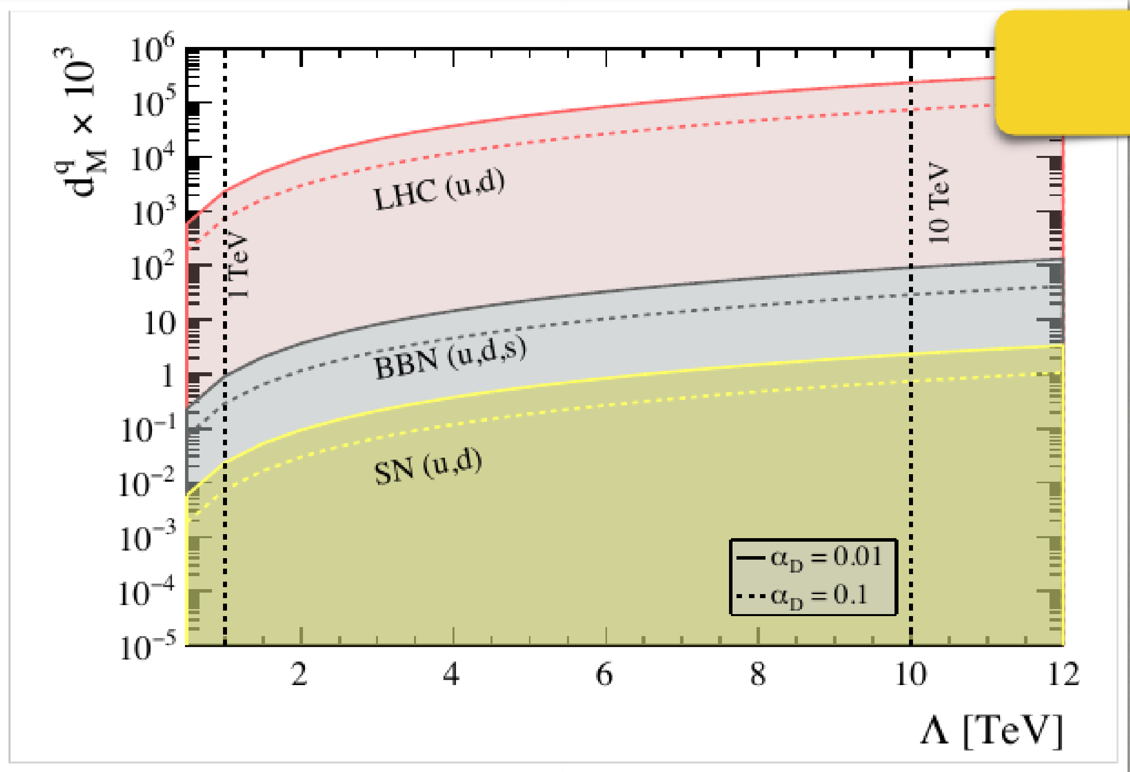
effective scale Λ

coupling to SM particles induced at 1-loop

[hep-ph/0411004]

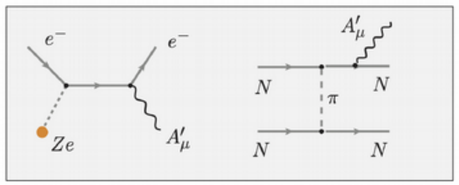
only **massive** dark-photon can have tree-level couplings with SM fermions via kinetic mixing

massless dark photon



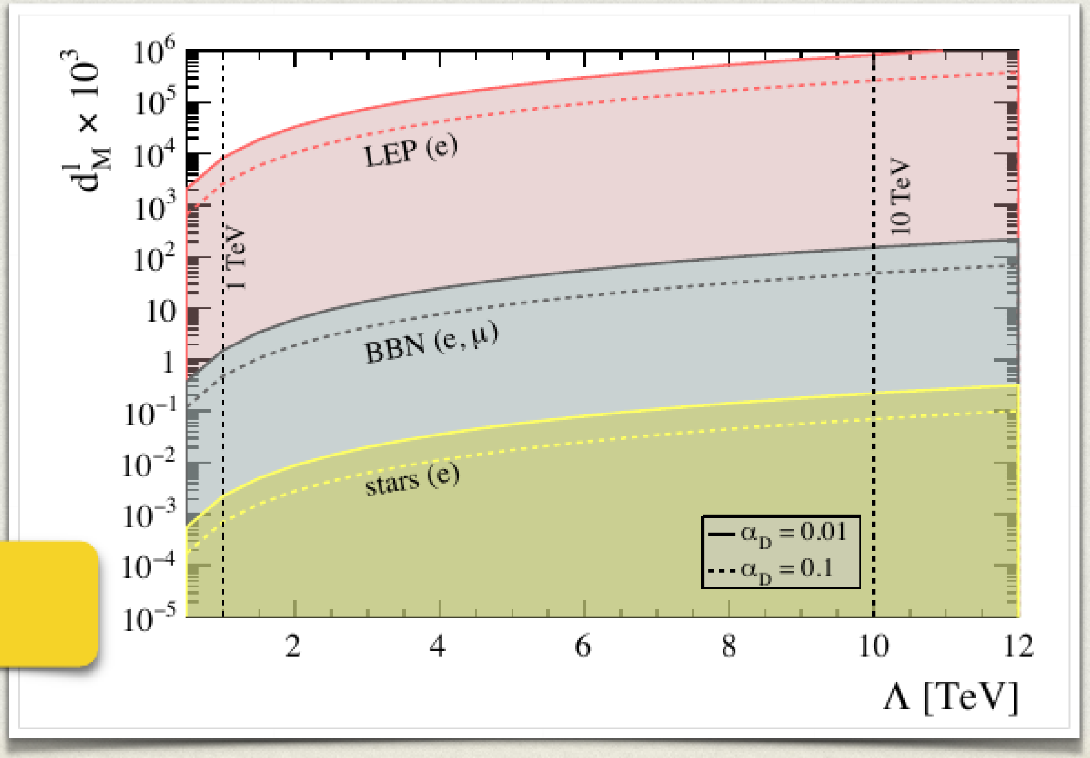
quarks

[from arXiv:2005.01515]



Bremsstrahlung of massless DP from electrons in a star and from nucleons in a supernova

leptons



BBN • Big bang nucleosynthesis. A cosmological bound for the dark photon operator comes from the determination of the effective number of relativistic species in addition to those of the SM partaking in the thermal bath—the same way the number of neutrinos is constrained.

SN • Supernovae. An additional limit is found from the neutrino signal of supernova 1987A, for which the length of the burst constrains anomalous energy losses in the explosion.

Massless DP couplings to neutral boson sector of SM

- Not constrained by astrophysics bounds
- Effective couplings to Higgs boson → dimension 5 operators → UV non-decoupling !
- Effective couplings to Z boson → dimension 6 operators → UV decoupling

massless DP signatures at colliders

EG, Heikinheimo, Mele, Raidal, PRD 90 (2014)
Biswas, EG, Heikinheimo, Mele PRD 93 (2016), PRD 96 (2017)
Biswas, EG, Mele, Symmetry 2002, 14 (8), 15222

main discovery channels

LHC $$H \to \gamma\,\gamma_D \to \gamma + \not{E}_T$$

FCC-ee $$e^+e^- \to H\gamma_D$$

FCC-ee $$e^+e^- \to ZH \to Z(H \to \gamma\gamma_D)$$

$\to$ **non decoupling features**

- **via Z decay** $$Z \to \gamma\,\gamma_D$$ $\to$ evading Landau-Yang theorem

Fabbrichesi, EG, Mele PRL 120 (2018)

- **Via** $$e^+e^- \to \gamma\,\gamma_D \to \gamma + \not{E}$$

Casarsa, Fabbrichesi, EG, PRD 105 (2022)

Via electron magnetic-dipole couplings

other DP productions mechanisms

- Via FCNC processes $f \to f' \, \gamma_D \quad f = t, b, c, s, \tau, \mu$

  EG, Mele, Raidal, Venturini, PRD 94 (2016)

- Via polarized muon decay $\mu^+ \to e^+ + \gamma_D$

  → possibility to disentangle spin via measurement of positron polarization

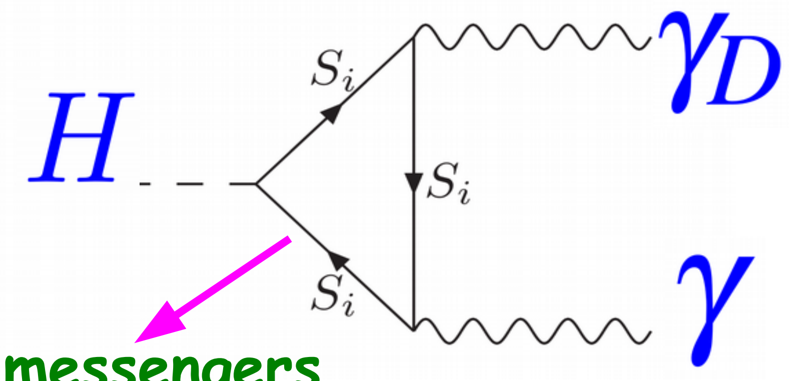
  Fabbrichesi, EG, PRD 104 (2021)

- relevant for NA62 $K^+ \to \pi^+ \pi^0 \, \gamma_D$ Fabbrichesi, EG, Mele, PRL 119 (2017)

Monophoton Exotic Higgs Signature

EG, Heikinheimo, Mele, Raidal, PRD 90 (2014)

$$H \to \gamma\, \gamma_D$$



scalar messengers

DP field strentgh

$$\mathcal{L}_{\mathrm{DP_H}} \simeq \frac{\alpha}{\pi}\left(\frac{C_{\gamma\gamma_D}}{v} F^{\mu\nu} F^D_{\mu\nu} H + \frac{C_{Z\gamma_D}}{v} Z^{\mu\nu} F^D_{\mu\nu} H + \frac{C_{\gamma_D\gamma_D}}{v} F^{D\,\mu\nu} F^D_{\mu\nu} H\right)$$

$$C_{Z\gamma_D} = R_{Z\gamma} C_{\gamma\gamma_D}$$

$$R^q_{Z\gamma} \simeq 0.79$$
$$R^l_{Z\gamma} \simeq 0.045$$

(small mixing ξ limit)

$$C_{\gamma\gamma_D} = \sqrt{\frac{\alpha_D}{\alpha}} \sum_{i=q,l} \frac{R_1^i}{12} \frac{\xi_i^2}{1-\xi_i^2}$$

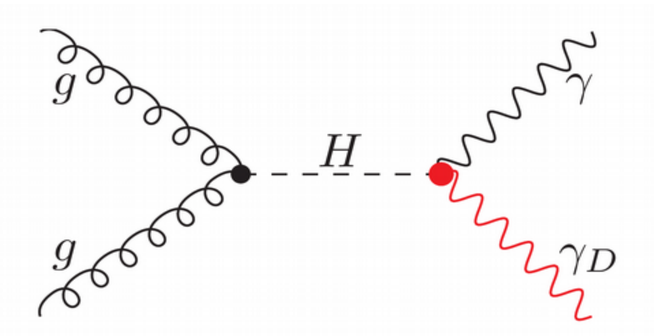
R_1 = product of U(1) charges

$\xi \to$ mixing parameter in scalar sector <1, potentially large

- non-decoupling effect in some UV limit $\to$ effective scale prop. to Higgs vev !
- dark-fine structure constant α_D could be large (allowed if DP is massless)
- contribute also to $H \to \gamma\gamma$ and $H \to g\, g$ (from Higgs production $\to \xi < 0.88$)

$H \to \gamma\gamma_D$ at LHC

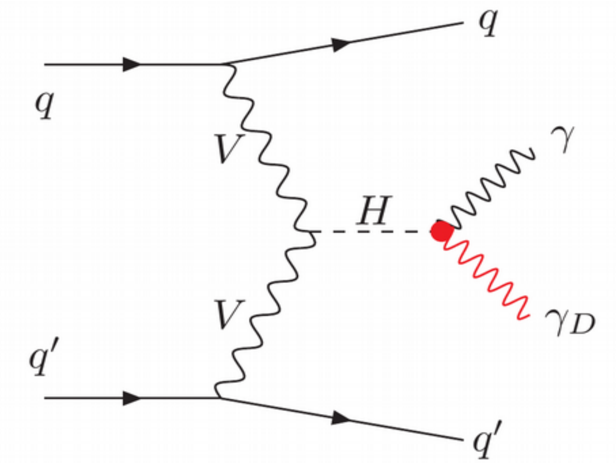
- **DP production mechanisms @ LHC**



gluon-gluon fusion → gg + VBF analyzed in
EG, Heikinheimo, Mele, Raidal, PRD 90 (2014)
Biswas, EG, Heikinheimo, Mele PRD 93 (2016)

$$pp \to \gamma + \not{E}_T$$

Challenging → large QCD bckg of jets faked as $\not{E}_T$

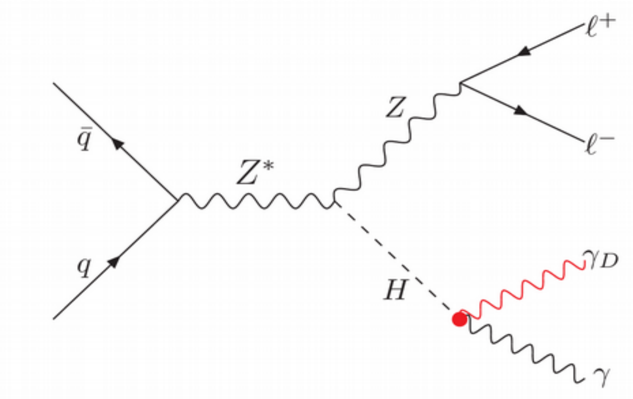


Vector Boson fusion

FB

$$pp \to \gamma + \not{E}_T + jets$$

ATLAS, CMS
run2



Z associated production

ATLAS, CMS
run2

$$pp \to ZH \to (Z \to \ell^-\ell^+)(H \to \gamma\gamma_D)$$

BR predictions in a simplified model (1 messenger) for $H \to \gamma\gamma_D$

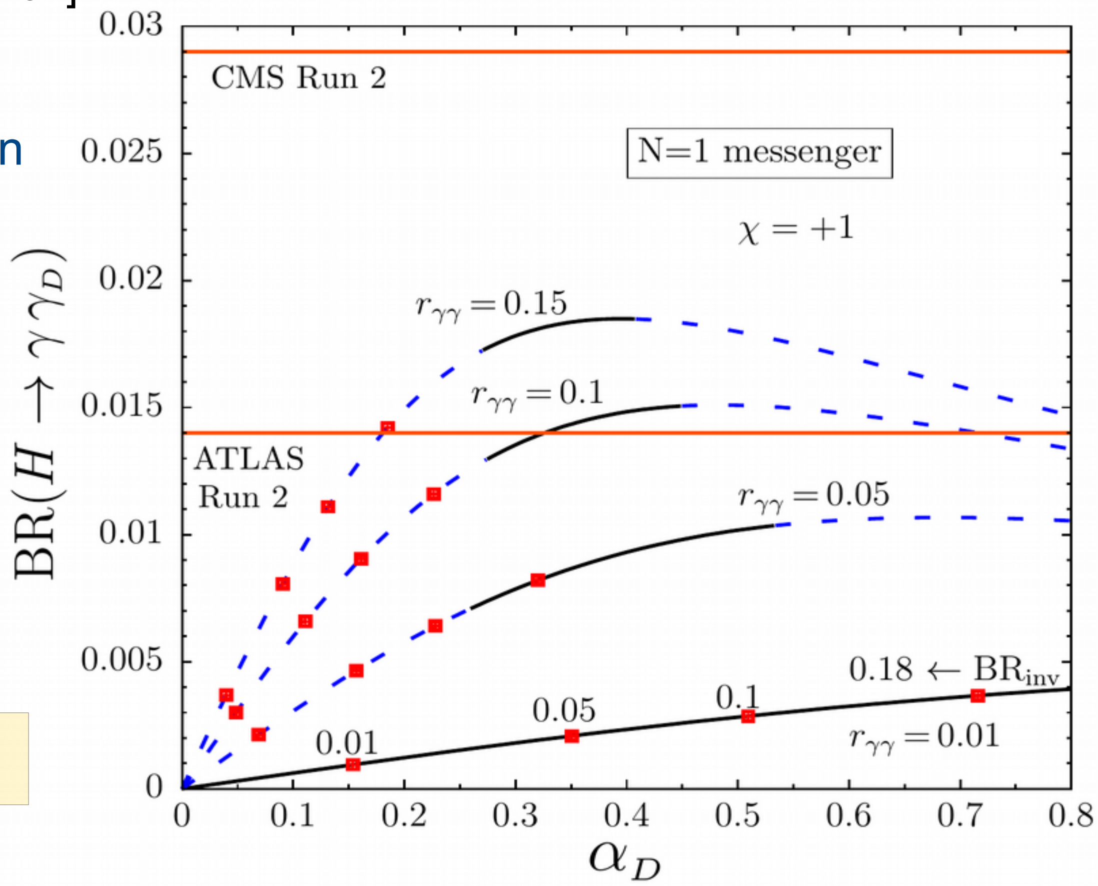
Biswas,EG,Mele [arXiv:2206.05297]

pure messenger NP contribution

$$r_{\gamma\gamma} = \frac{\Gamma^{\rm m}(H \to \gamma\gamma)}{\Gamma^{\rm SM}(H \to \gamma\gamma)}$$

χ=+1 → interference construttive with SM

allowed regions BR < 1%



observed upper limits @ 95% C.L.

CMS → BR < 2.9 %
[arXiv:2009.14009]

ATLAS → BR< 1.4 %
[arXiv:2109.00925]

excluded by $H \to \gamma\gamma$ @ 95% C.L.

FUTURE PERSPECTIVES @ LHC and future hadron colliders

$\mathrm{BR}_{\gamma\gamma_D}$ (%)	3 ab^{-1}@14 TeV		15 ab^{-1}@27 TeV	
significance	2σ	5σ	2σ	5σ
CMS inspired	0.012	0.030	0.0052	0.013

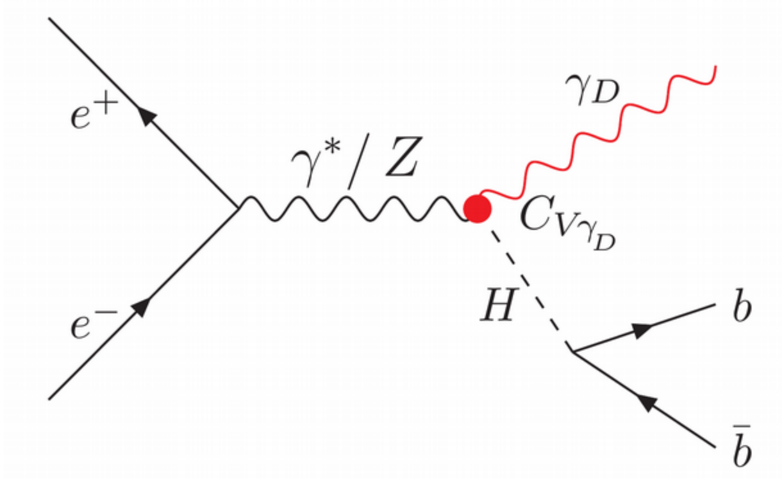
from [arXiv:2206.05297]

sensitive to allowed regions

DP production at Future e+e- colliders

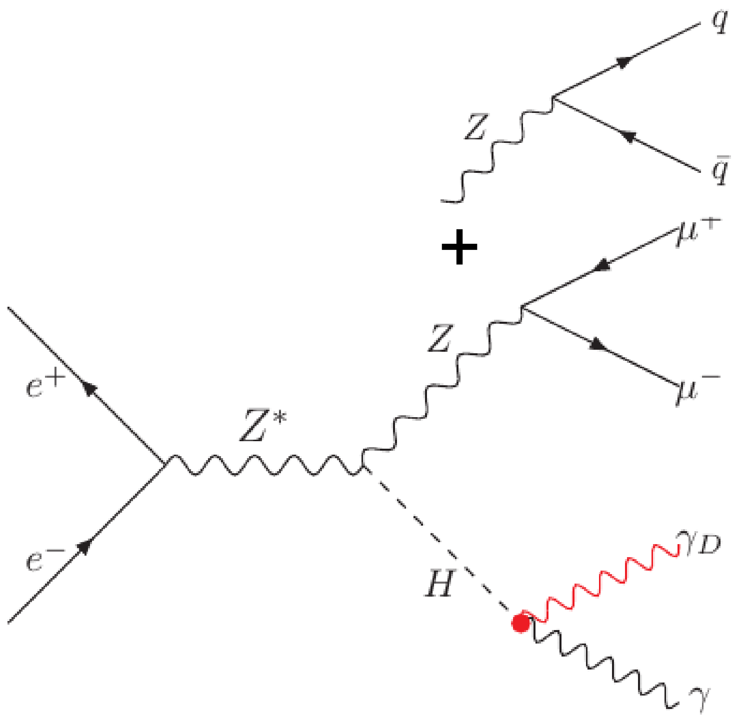
improved sensitivity on Higgs-photon-DP coupling

$$e^+e^- \to H\gamma_D$$



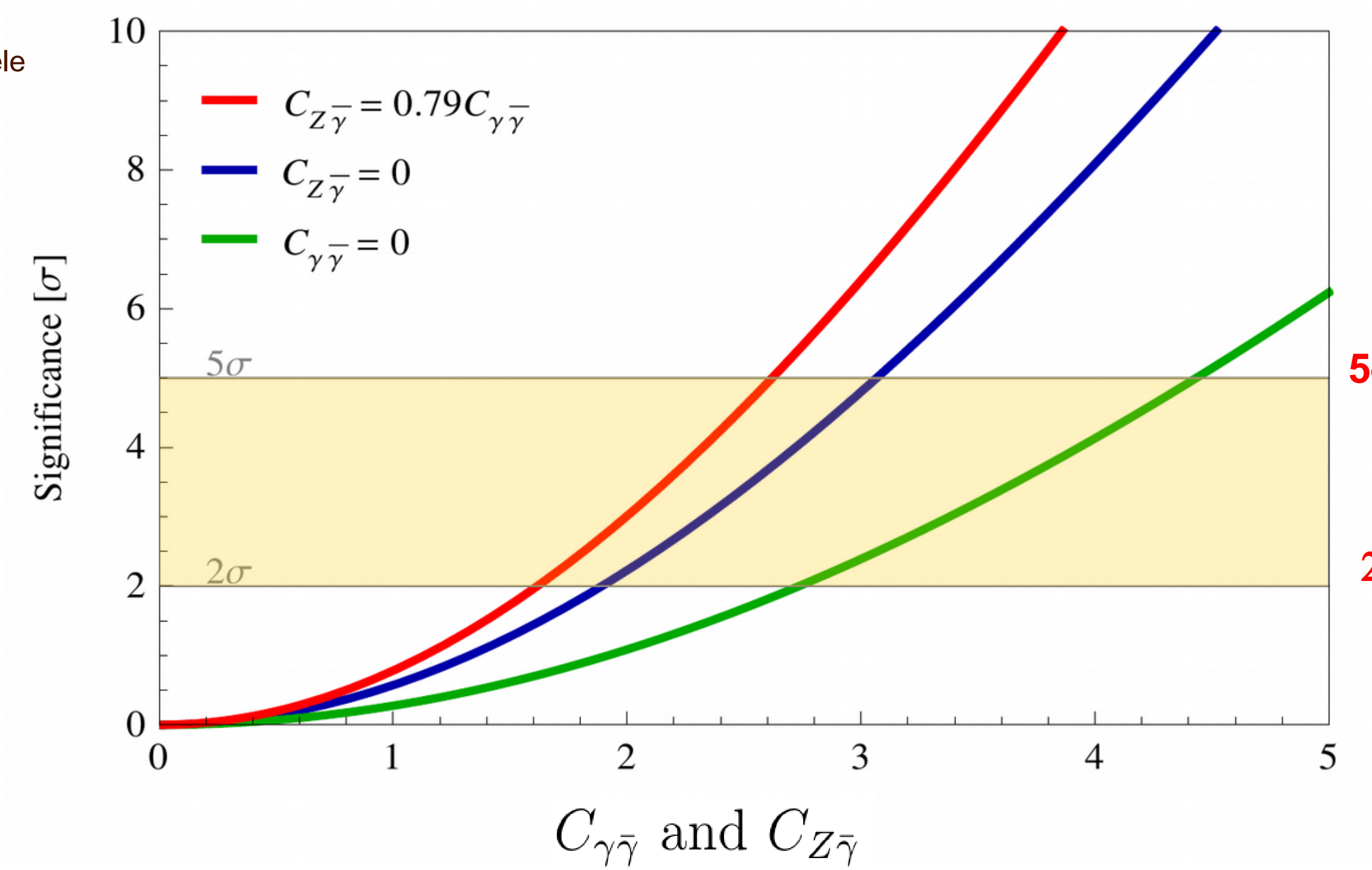
provides a better sensitivity

$$e^+e^- \to ZH \to Z(H \to \gamma\gamma_D)$$



$e^+e^- \to H\bar{\gamma} \to b\bar{b}\bar{\gamma}$ $\sqrt{s}$ =240 GeV

Biswas, EG, Heikeinheimo, Mele
JHEP 06 (2015) [arXiv:1503.05386]



L=10ab-1

5σ

2σ

$C_{\gamma\bar{\gamma}} > 1.9$ ⇨ $\mathrm{BR}(H \to \gamma\bar{\gamma}) > 3\,\mathrm{BR}_{SM}(H \to \gamma\gamma)$ ~ 6×10^{-3}

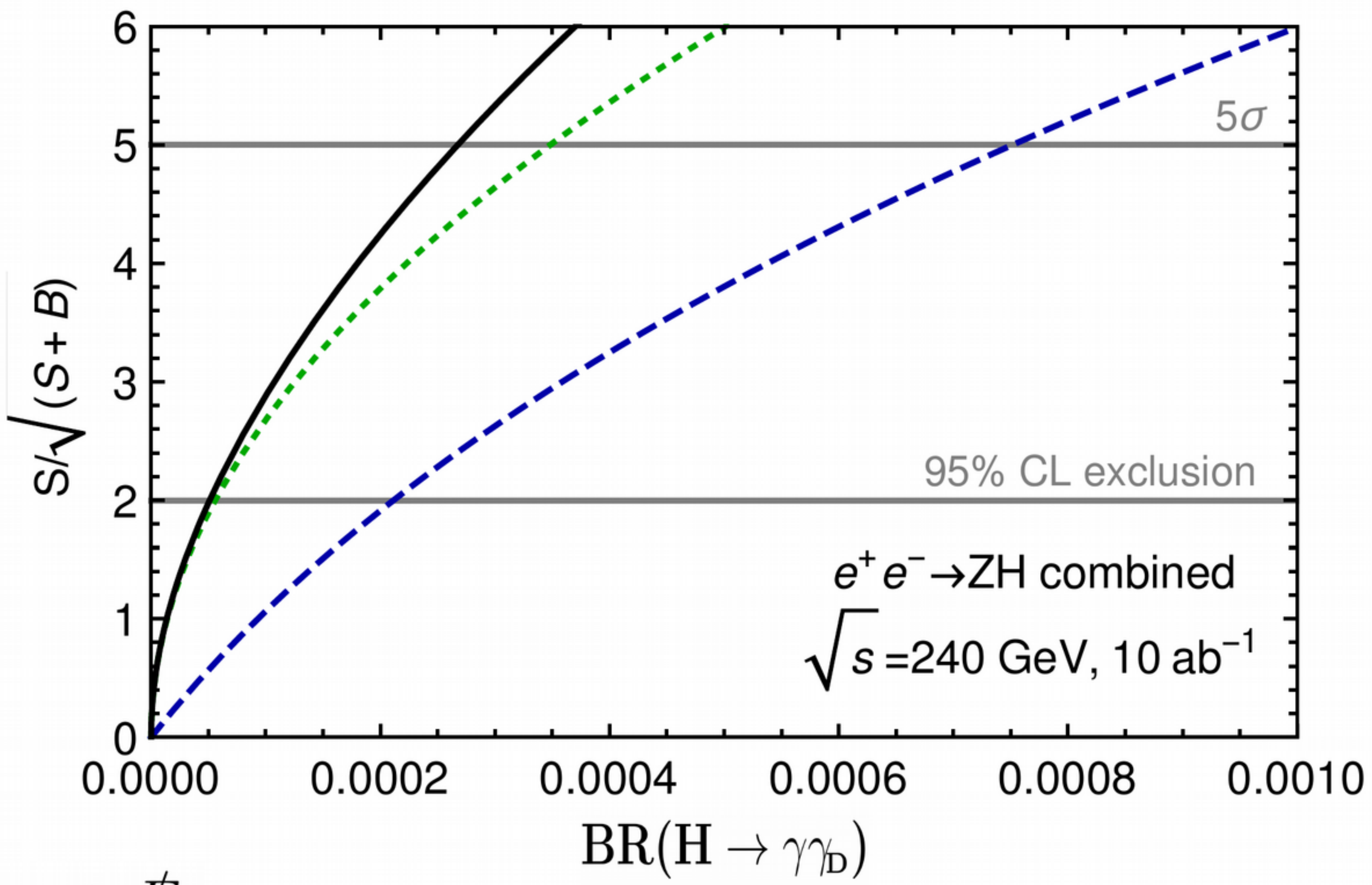
$C_{Z\bar{\gamma}} > 2.7$ ⇨ $\mathrm{BR}(H \to Z\bar{\gamma}) > 9\,\mathrm{BR}_{SM}(H \to Z\gamma)$

$$e^+e^- \to ZH \to (\mu^+\mu^-, q\bar{q})(\gamma\bar{\gamma})$$

Biswas, EG, Heikeinheimo, Mele, PRD 96 (2017)

$\sqrt{s} = 240$ GeV

L=10ab-1



dimuon+$\gamma + \not{E}$

dijet+$\gamma + \not{E}$

combined

$Z \to \gamma + X$

- Main characteristic signature:
  - isolated mono-chromatic photon ($E_\gamma \sim M_Z/2$) + missing energy (neutrino-like)

- Best place to look for: e+ e- colliders as FCC-ee

$$e^+e^- \to Z \to \gamma + X$$

  - monochromaticity of photon mostly maintained (Z peak), slightly spread by initial beam radiation

- <u>once a signal is observed</u> → possible to disentangle dark-photon from other scenarios that could mimic same signature

- X light boson invisible decays
  - **spin-1** (Dark-Photon)
  - **spin-0** (ALP → effective couplings $\gamma\gamma$ and $Z\gamma$)
  - **spin-2** (like KK gravity with low energy scale),..

generated at 1-loop, sensitive to dark magnetic-dipole couplings of all SM fermions

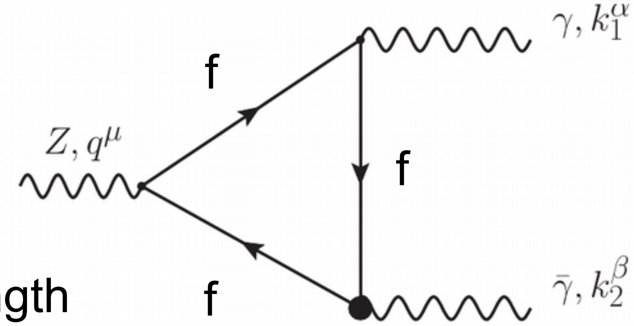
$$Z \rightarrow \gamma\bar{\gamma}$$

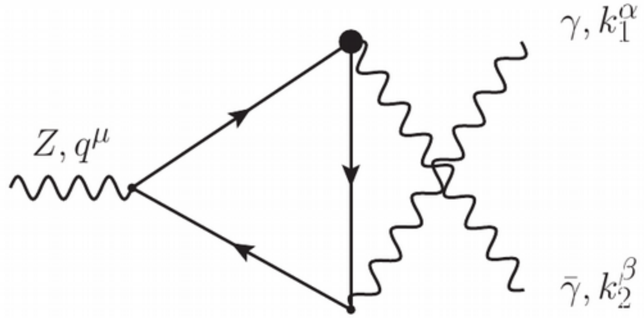
Fabbrichesi, EG, Mele PRL 120 (2018)]

f $\rightarrow$ run over all SM fermions

$$\mathcal{L} = \sum_f \frac{e_D}{2\Lambda} \bar{\psi}_f \sigma_{\mu\nu} \left(d_M^f + i\gamma_5 d_E^f \right) \psi_f B^{\mu\nu}$$

dark photon field strength





- Landau-Yang theorem forbids Z $\not\rightarrow$ 2 photons $\rightarrow$ amplitude vanishes
  avoided due to distinguishability of photon and dark-photon interaction vertices (blob)

- massive dark-photon couples also via magnetic dipole interaction

- tree-level coupling of massive DP via mixing with photon is vanishing due to LY theorem

$$\mathcal{L}_{eff} = \frac{e}{\Lambda M_Z} \sum_{i=1}^{3} C_i \mathcal{O}_i(x)$$

C_i finite due gauge invariance

dimension-six operators $\mathcal{O}_i$ are

$$\begin{aligned} \mathcal{O}_1(x) &= Z_{\mu\nu} \tilde{B}^{\mu\alpha} A^{\nu}{}_{\alpha}\,, \\ \mathcal{O}_2(x) &= Z_{\mu\nu} B^{\mu\alpha} \tilde{A}^{\nu}{}_{\alpha}\,, \\ \mathcal{O}_3(x) &= \tilde{Z}_{\mu\nu} B^{\mu\alpha} A^{\nu}{}_{\alpha}\,. \end{aligned}$$

Dark-U(1) charge

$$\mathcal{L} = \sum_f \frac{e_D}{2\Lambda} \bar{\psi}_f \sigma_{\mu\nu} \left(d_M^f + i\gamma_5 d_E^f \right) \psi_f B^{\mu\nu}$$

$d_M \simeq 1/2$
$\rightarrow$ large but perturbative couplings in DS

$$\mathrm{BR}(Z \to \gamma\bar{\gamma}) \simeq \frac{2.52\, \alpha_D}{(\Lambda/\mathrm{TeV})^2} \left(|d_M|^2 + |d_E|^2\right) \times 10^{-8}$$

10^{-9}

$\alpha_D \rightarrow$ 0.1
$\Lambda \rightarrow$ 1 TeV

4×10^{-11}

$d_M \simeq 0.1$
$\rightarrow$ small couplings in DS

LEP upper bound of $\mathrm{BR}(Z \to \gamma\bar{\gamma}) \simeq 10^{-6}$

M. Acciarri *et al.* [L3 Collaboration], Phys. Lett. B **412**, 201 (1997); O. Adriani *et al.* [L3 Collaboration], Phys. Lett. B **297**, 469 (1992); P. Abreu *et al.* [DELPHI Collaboration], Z. Phys. C **74**, 577 (1997); R. Akers *et al.* [OPAL Collaboration], Z. Phys. C **65**, 47 (1995).

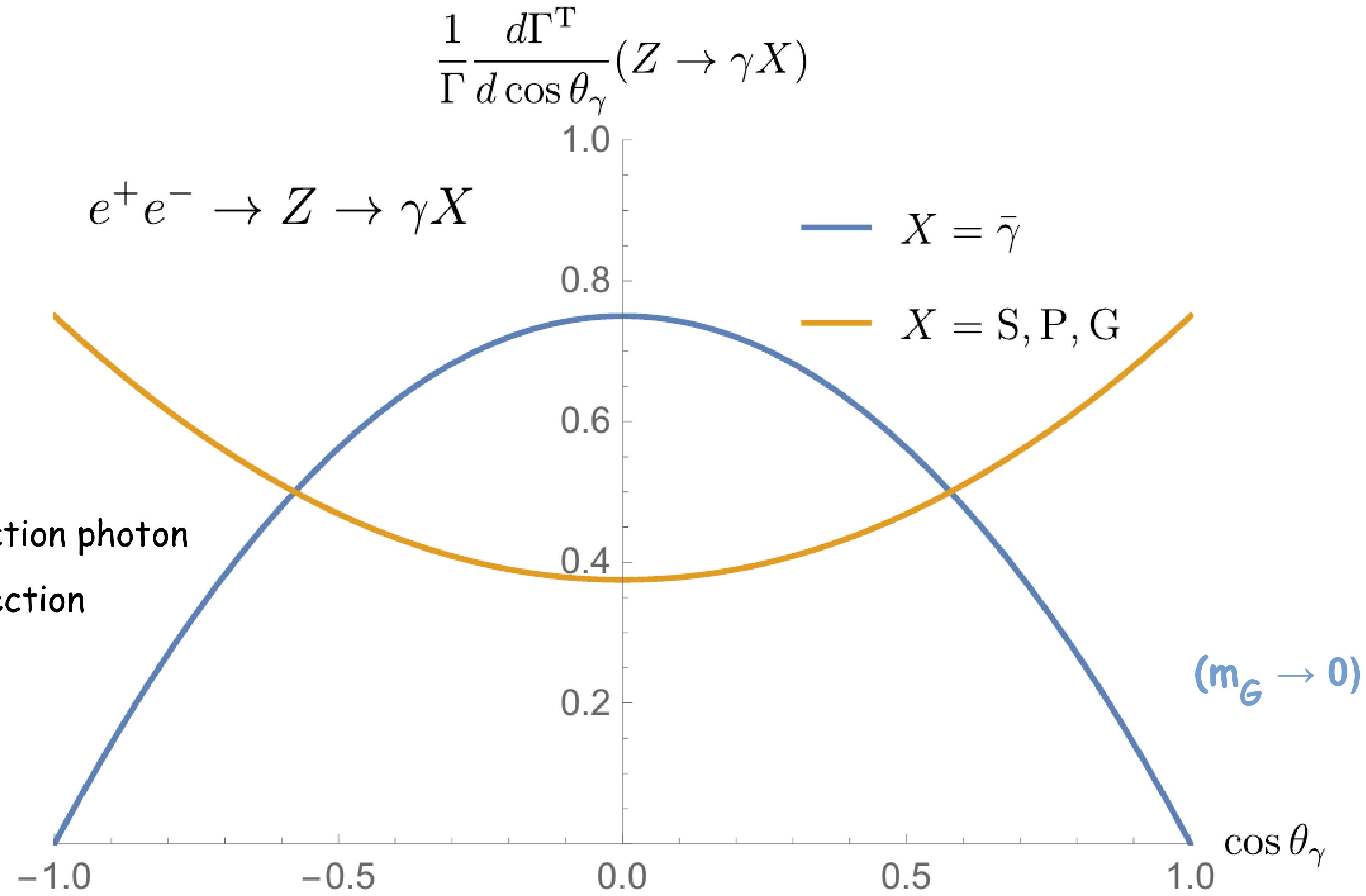
10^{-6} $\rightarrow$ for non-perturbative dynamics in DS

RESULTS $\rightarrow$

10^{13} of Z boson events at the FCC-ee

expected 10^2–10^4 of $Z \to \gamma\bar{\gamma}$ events

A. Comelato, EG (2020)



θ_γ angle between direction photon and initial e- beam direction

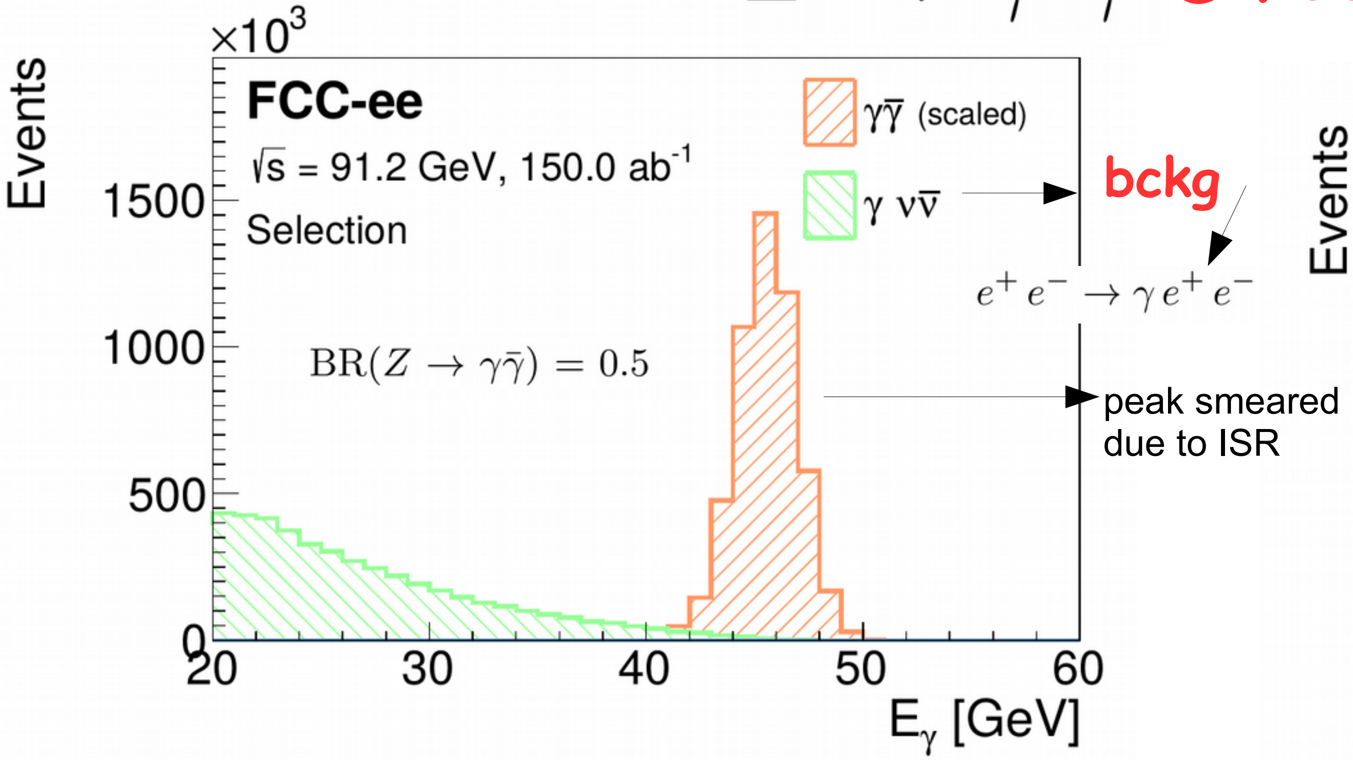
A. Comelato, EG (2020)

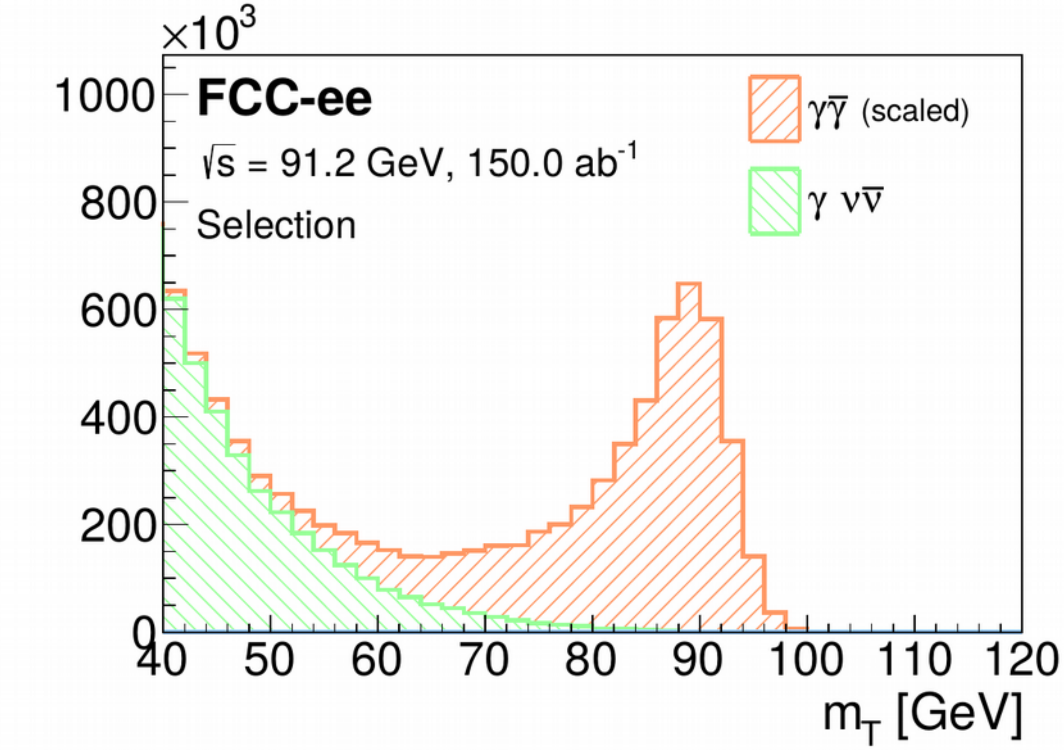
X spin can be disentangled → spin-1: photon mainly produced central and at large angles

spin-0/2: " " " along Forward-Backward dir.

$Z \to \gamma\,\bar{\gamma}$ @ FCC-ee

Cobal, De Dominicis, Fabbrichesi, EG, J. Magro, Mele, Panizzo (2020) [arXiv:2006.15945]





transverse invariant mass simplifies here $M_T = 2p_T^\gamma$

upper limits on BR at 95% C.L.

			$\mathrm{BR}(Z \to \gamma\bar{\gamma})$	
	$\sqrt{s}$	L (ab^{-1})	M_T	E_γ
LHC	13 TeV	0.14	8×10^{-6}	5×10^{-5}
HL-LHC	13 TeV	3	2×10^{-6}	1×10^{-5}
FCC-ee	91.2 GeV	150	2×10^{-11}	3×10^{-11}
CEPC	91.2 GeV	16	7×10^{-11}	8×10^{-11}

Spin analysis using test statistics

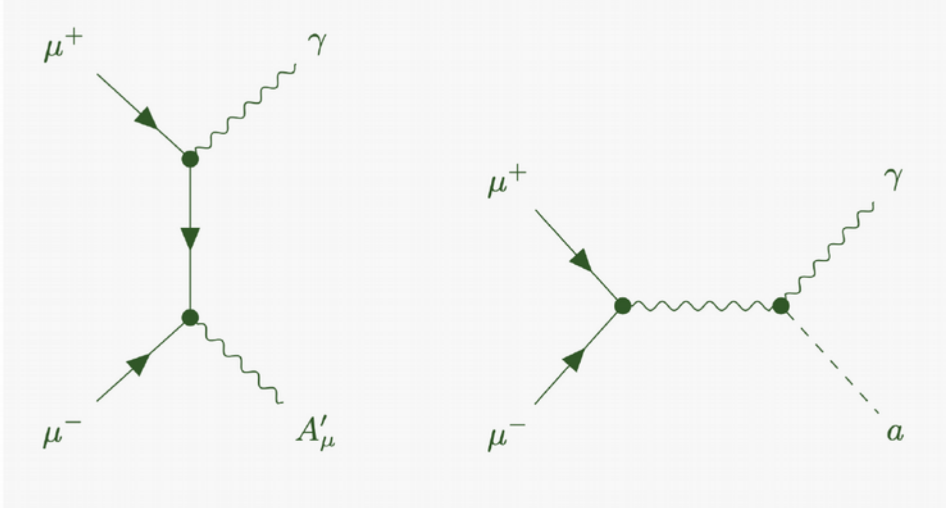
N=6 (N=17) → lower bound for expected (observed) N. of signal events needed to exclude the hypothesis under the $p_0(J^P = 1^-)$ assumption at 95% C.L.

Mono-chromatic single photon events at the muon collider

Casarsa, Fabbrichesi, EG, PRD 105 (2022)

results can be extended to e+e- @ FCC-ee

$$\mu^+\mu^- \rightarrow \gamma\gamma_D$$

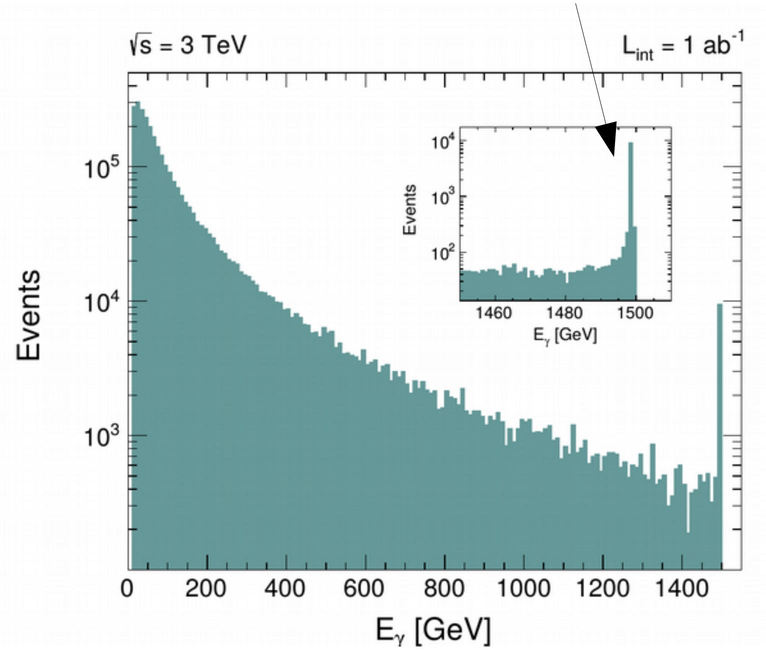


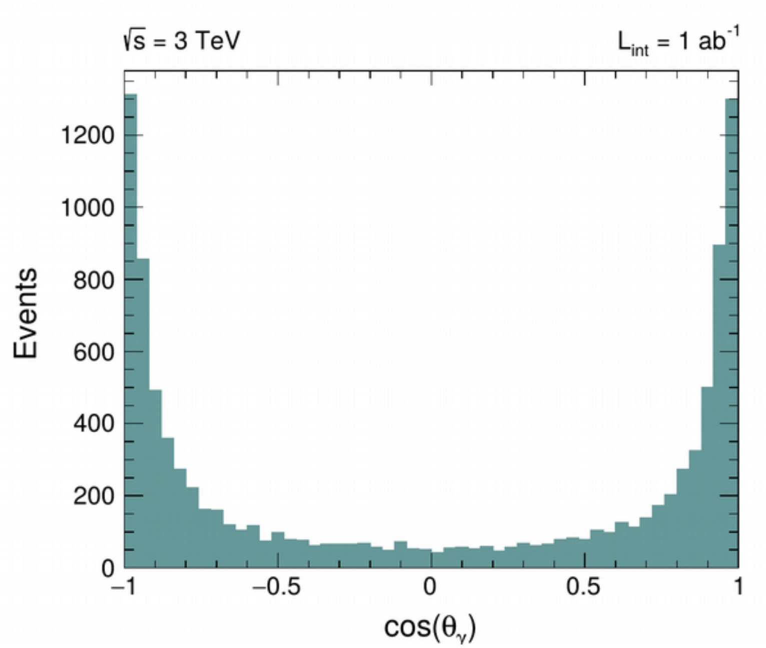
SM background

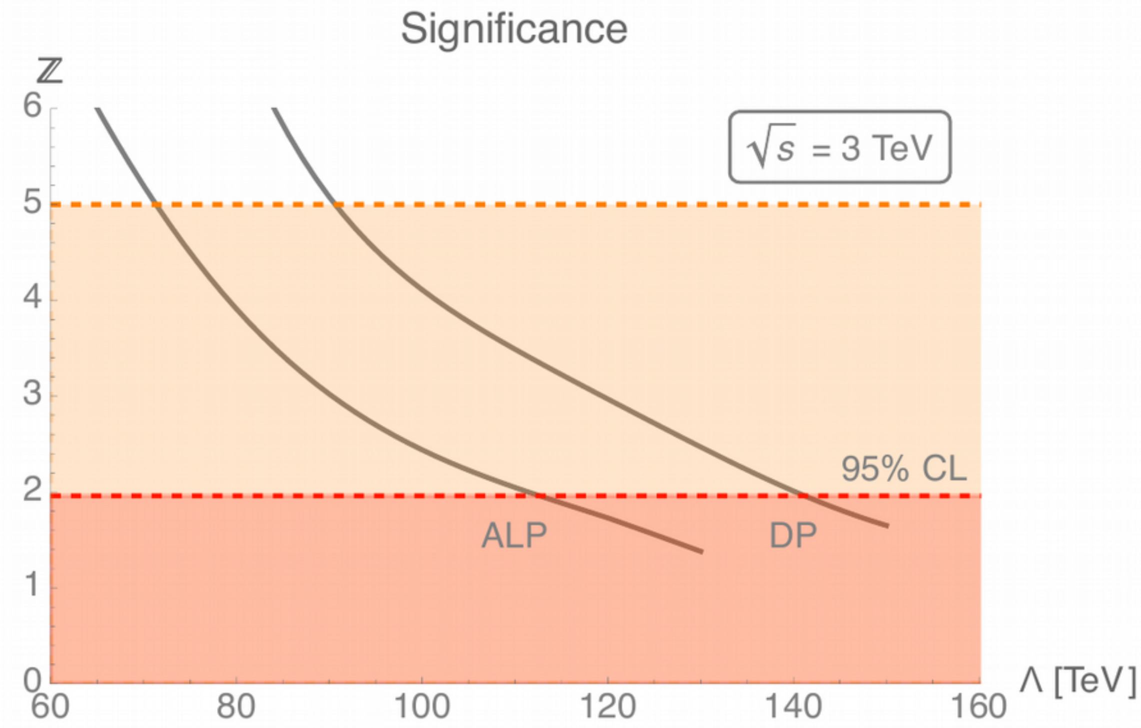
$$\mu^+\mu^- \rightarrow \gamma\nu\bar{\nu}$$

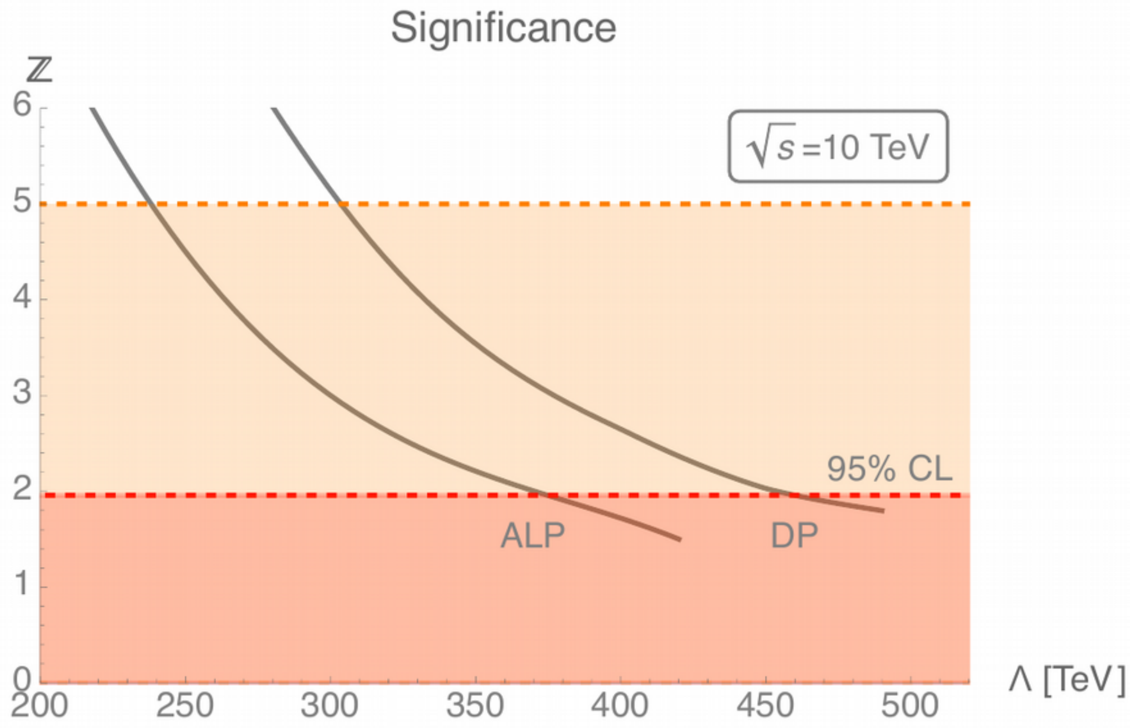
Z-radiative return effect → $E_\gamma = \frac{\sqrt{s}}{2}\left(1 - \frac{m_Z^2}{s}\right)$

Signal almost on same region → $\boxed{E_\gamma = \frac{\sqrt{s}}{2}}$









	$\sqrt{s} = 3$ TeV		$\sqrt{s} = 10$ TeV	
	DP	ALP	DP	ALP
Limit	141 TeV	112 TeV	459 TeV	375 TeV
Discovery	92 TeV	71 TeV	303 TeV	238 TeV

$$\mathcal{L}_{\rm DP}^{\rm dipole} = \frac{1}{2\,\Lambda}\left(\bar{\mu}\,\sigma_{\mu\nu}\,\mu\right) F'^{\mu\nu}$$

DP field strength

Conclusions

- FCC has a great potential to constrain or discover dark sector, via existence of portals: dark-Higgs, ALP, sterile-neutrino, dark-photon, ..etc

- High mass regions in New Particle portals probed with respect to low energy experiments

- Most of present and future experimental searches focused on massive dark-photons

- Massless dark-photon scenario less constrained $\rightarrow$ different signatures required

- $H \to \gamma\, \gamma_D$ promising channel at LHC and FCC due to potential non-decoupling

- $\mathrm{BR}(H \to \gamma\gamma_D) \sim 10^{-4} - 10^{-3}$ probed @ FCC-ee via $e^+e^- \to ZH \to (\mu^+\mu^-, q\bar{q})(\gamma\bar{\gamma})$

- FCC-ee can probe $Z \to \gamma\, \gamma_D$ $\rightarrow$ expected 10^2–10^4 of $Z \to \gamma\bar{\gamma}$ events