Feebly-interacting particles: Experimental Prospects

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European Strategy Update

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Preamble

✓ Efforts concentrated so far on high-mass, strongly-coupled sector:

⟶ TeV scale generically motivated by naturalness arguments

⟶ This paradigm motivates direct searches at (high-energy) colliders, BSM effects in flavor (loops) and direct DM detection experiments (WIMP paradigm).

⟶ Lack of unambiguous signal of NP so far calls for investigating also new paradigms.

✓ Feebly-interacting particles are generically motivated (see G. Perez's talk):

⟶ their investigation has been so far discontinuous and parasitic to other (main) physics programs.

✓ We need a systematic investigation of the "feeble front".

Outstanding Questions in Particle Physics: the "feeble front"

A (very) limited list of examples

Experimental facts

Dark Matter:
candidates \w mass from 10^{-22} eV (light feeble scalars) to 10^{20} GeV (black holes).
⟶FIPs: if DM is a thermal relic, then mass is restricted o(10) keV – 100 TeV: MeV-GeV DM requires light mediators

Neutrino masses and oscillations
explanation: RH neutrinos with masses from 10^{-2} eV to 10^{15} GeV.
⟶FIPs: If RHN have generic (feeble) Yukawa's + approximate $U(1)_L$, masses can be below EW scale.

Matter-antimatter asymmetry
hard to associate scale, solutions of many orders of magnitudes:
⟶FIPs: baryogenesis could occur via CPV relaxion-Higgs couplings;
⟶FIPs: baryogenesis could occur via leptogenesis via neutrino oscillations of RHN with masses below EW scale.

Theoretical

Naturalness problem:
Symmetry-based solutions => TeV partners;
⟶FIPs: relaxion => light feeble Goldstone bosons (ALPs)

Strong CP problem:
⟶FIPs: axion = light feeble Goldstone boson;

………

See P. Hernandez, opening talk and G. Perez talk.

Feeble interacting particles are generically motivated
in broad class of models.
But their mass scale is unknown.

We need a multi-scale (and multi-experiment) approach.

How to search for such broad class of models?
Use simplified models.

How to compare frontiers, experiments?
Use benchmarks.

Simplified (simplest?) models: the four portals

HNLs, LDM & Light mediators, ALPs must be SM singlets, hence options limited by SM gauge invariance: According to generic quantum field theory, the lowest dimension canonical operators are the most important:

Portal	Coupling
Dark Photon, A_μ	$-\frac{\epsilon}{2\cos\theta_W} F'_{\mu\nu} B^{\mu\nu}$
Dark Higgs, S	$(\mu S + \lambda S^2) H^\dagger H$
Axion, a	$\frac{a}{f_a} F_{\mu\nu}\tilde{F}^{\mu\nu}$, $\frac{a}{f_a} G_{i,\mu\nu}\tilde{G}_i^{\mu\nu}$, $\frac{\delta_\mu a}{f_a}\overline{\psi}\gamma^\mu\gamma^5\psi$
Sterile Neutrino, N	$y_N L H N$

See also Murayama's (DM session) and Ceccucci's (Flavor session) talks.

From portals we can identify benchmark cases to evaluate the experimental sensitivities. A common ground to compare the proposals against each other and put them in worldwide context.

Four "lampposts" in the darkness of the orders of magnitude. A starting point.

Proposals considered in this study

collider	type	$\sqrt{s}$	$\mathcal{P}$ [%] $[e^+/e^-]$	N(det)	$\mathcal{L}$ [ab^{-1}]	time years
HL-LHC	pp	14 TeV	–	2	6	12
HE-LHC	pp	27 TeV	–	2	15	20
FCC-hh	pp	100 TeV	–	2	30	25
FCC-ee	e^+e^-	M_Z	0/0	2	150	4
		$2M_W$	0/0	2	10	1
		240 GeV	0/0	2	5	3
		$2\ m_{top}$	0/0	2	1.7	5
ILC	e^+e^-	250 GeV	$\pm80/\pm30$	1	2	11
		350 GeV	$\pm80/\pm30$	1	0.2	1
		500 GeV	$\pm80/\pm30$	1	4	7
CEPC	e^+e^-	M_Z	0/0	2	16	2
		$2M_W$	0/0	2	2.6	1
		240 GeV	0/0	2	5.6	7
CLIC	e^+e^-	380 GeV	$\pm80/0$	1	1.0	8
		1.5 TeV	$\pm80/0$	1	2.5	1
		3.0 TeV	$\pm80/0$	1	5.0	5
LHeC	ep	1.3 TeV	0/0	1	1.0	15
FCC-eh	ep	3.5 TeV	0/0	1	2.0	25

From Higgs WG report arXiv:1905.03764

+ beam-dump/fixed target experiments of the Physics Beyond Colliders Study group.

(arXiv:1901.09966).

WARNING

The level of maturity of the sensitivity plots is very different across the proposals.

Evaluation of geometrical acceptance, trigger, reconstruction, selection efficiencies and backgrounds are long-term projects.

The following sensitivity curves represent the current state-of-the-art provided by the Collaborations.

Vector portal
(Dark Photons)

$$-\frac{\varepsilon}{2\cos\theta_W} F'_{\mu\nu} B^{\mu\nu}$$

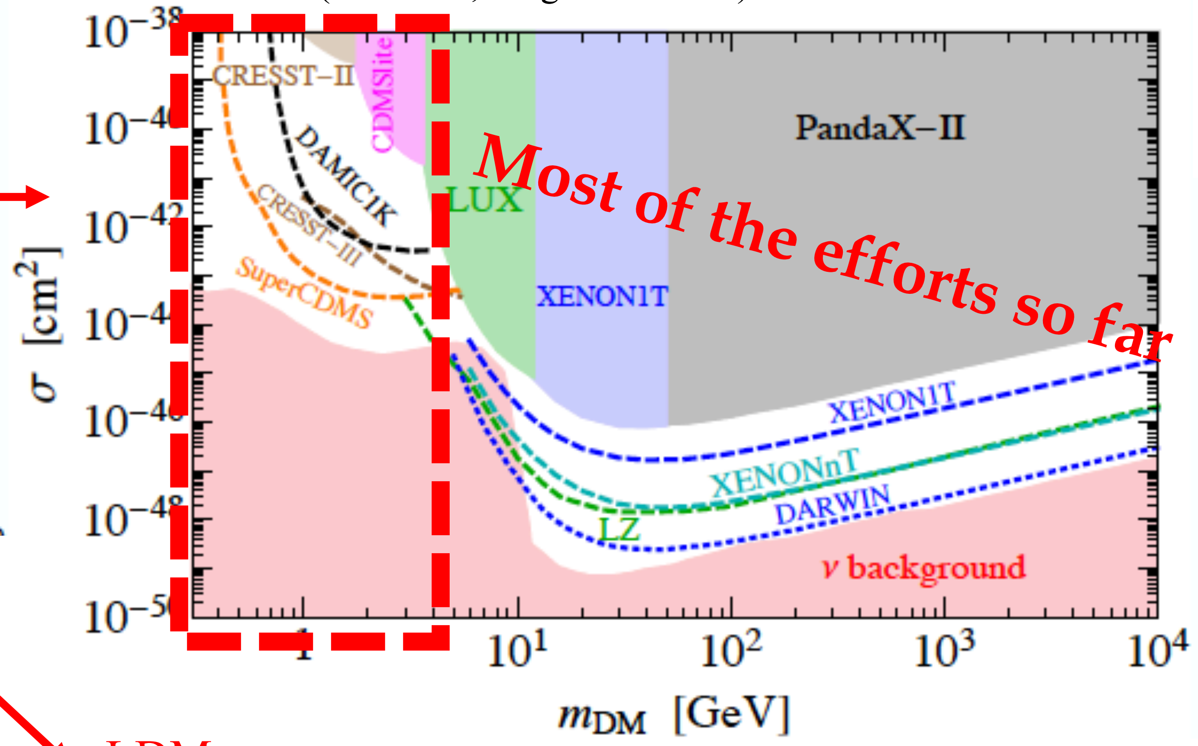
Okun, Voloshin , Holdom, Ellis, Schwarz, Tyupkin, Kolb, Seckel, Turner, Georgi, Ginsparg, Glashow, Foot, Volkas, Blinikov, Khlopov, Gninenko, Ignatiev, Batell, Pospelov, Ritz, Marciano, Altmannhofer, Gori, Essig, Papucci, Volansky, Arkani-Hamed, Gori, Shelton, Izaguirre…….and many others

Vector portal: a possible physics motivation: new (vector) mediators for (light) Dark Matter with thermal origin

DM candidates (and relative mediators) with thermal origin can have mass between 10 keV and 10 TeV.

(see Perez, Frugiuele's talks)

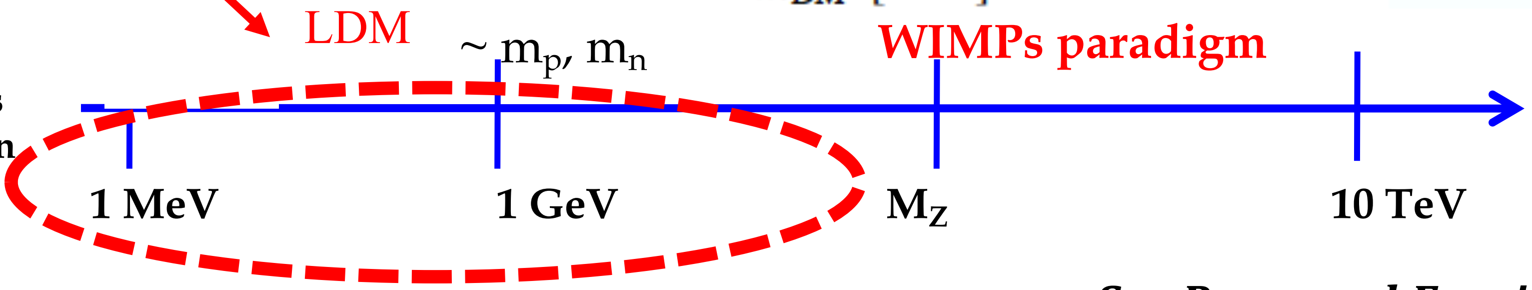
New Particles with masses in the MeV-GeV range and feebly-coupled to SM



$$\Omega_{DM}h^2 \sim \frac{10^9\ \mathrm{GeV}^{-1}}{M_{pl}} \frac{1}{\langle \sigma v \rangle}$$

$$\sigma v \sim \alpha_D \epsilon^2 \alpha \frac{m_\chi^4}{m_{A'}^4} \times \frac{1}{m_\chi^2}$$

< 10 keV
DM too hot, spoils structure formation

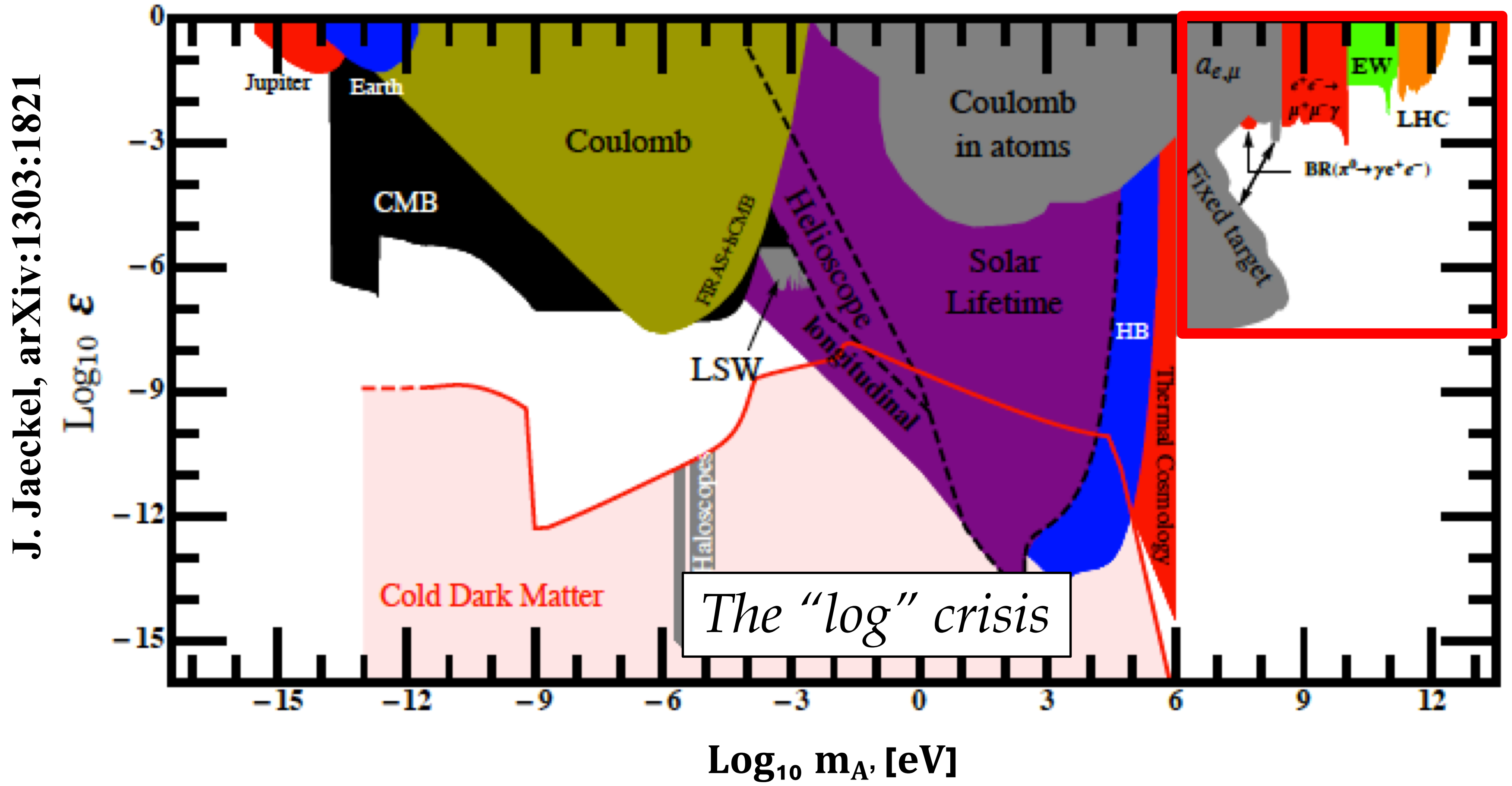


> 100 TeV
DM overproduced

See Perez and Frugiuele talks.

Vector portal: current limits in the Ɛ versus Dark Photon mass plane

Model where minimally coupled viable (WIMP-like) dark matter model can be constructed.
DM is charged under a broken $U(1)_D$ abelian gauge symmetry.
The parameter space for this model is $\{\alpha_D, \varepsilon, m_{A'}, m_\chi\}$.



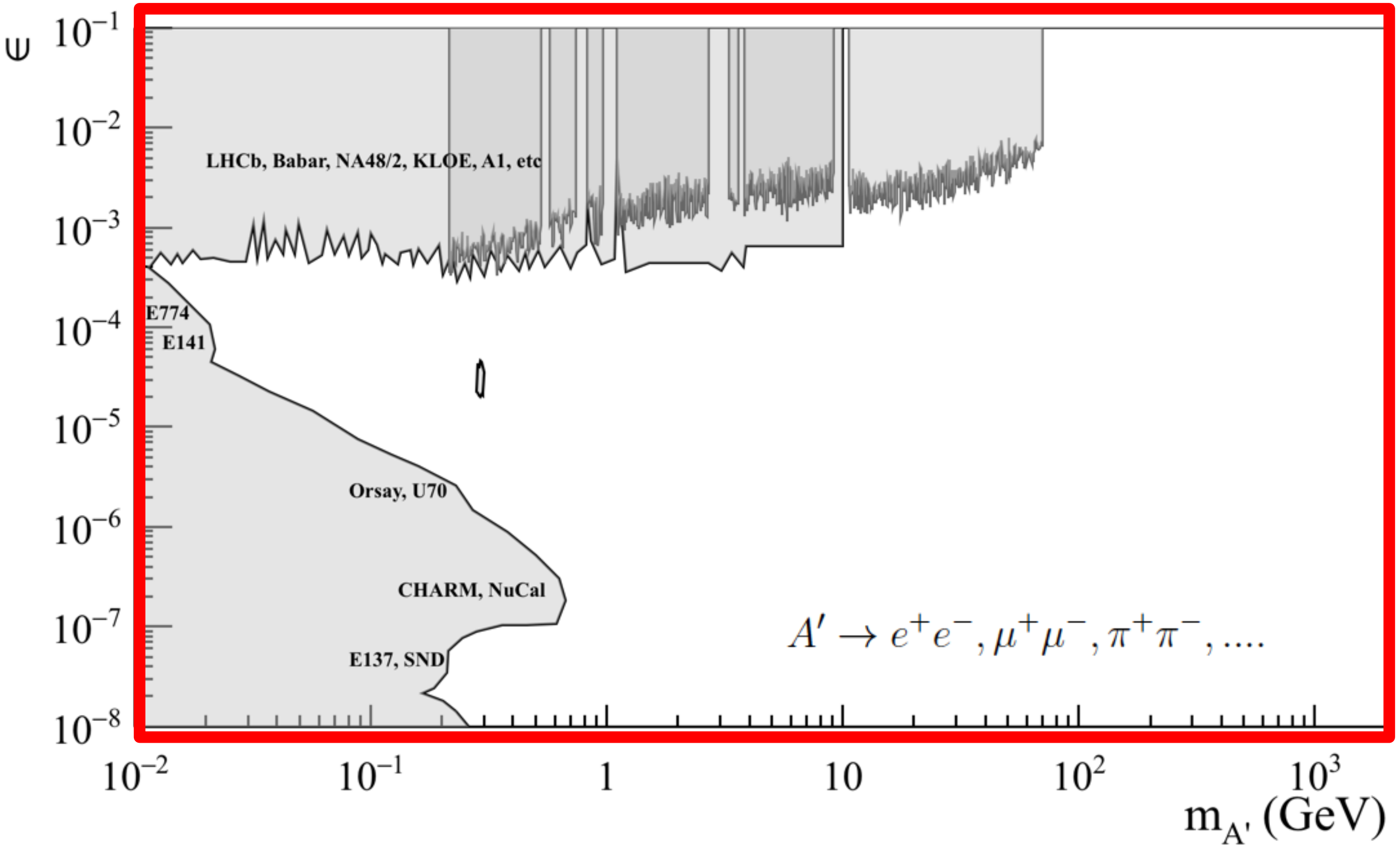
⇦ **MeV-TeV range accelerators' domain (range compatible with the hypothesis of DM as thermal relic)**

Several orders of magnitude involved: we need a multi-scale (multi-experiment) approach.

Vector Portal: Dark Photon coupled to SM particles

Existing 95% CL limits (accelerator based).

Zoom in the MeV-TeV range



Source:
Physics Beyond Colliders BSM report, arXiv:1901.09966.

Current limits provided by colliders, fixed-target and beam-dump experiments

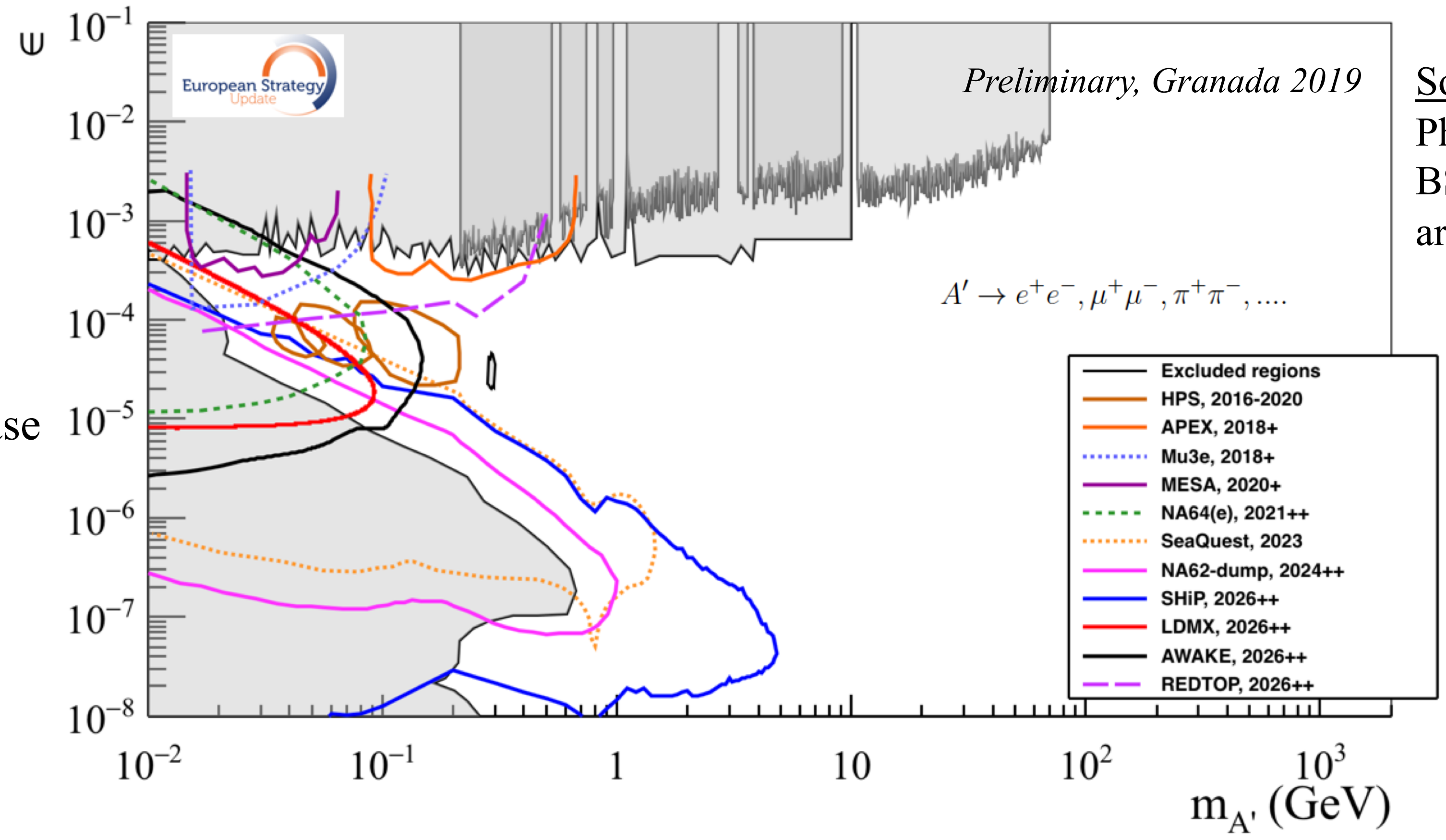
Vector Portal: Dark Photon coupled to SM particles

Prospects in the next 10-15 years for beam-dump/fixed target experiments.

For visible decays:

signal ∝ ϵ^4

x100 signal rate increase
x 3 improvement in Ɛ



Source:
Physics Beyond Colliders BSM report, arXiv:1901.09966.

See Graverini, Vallee talks

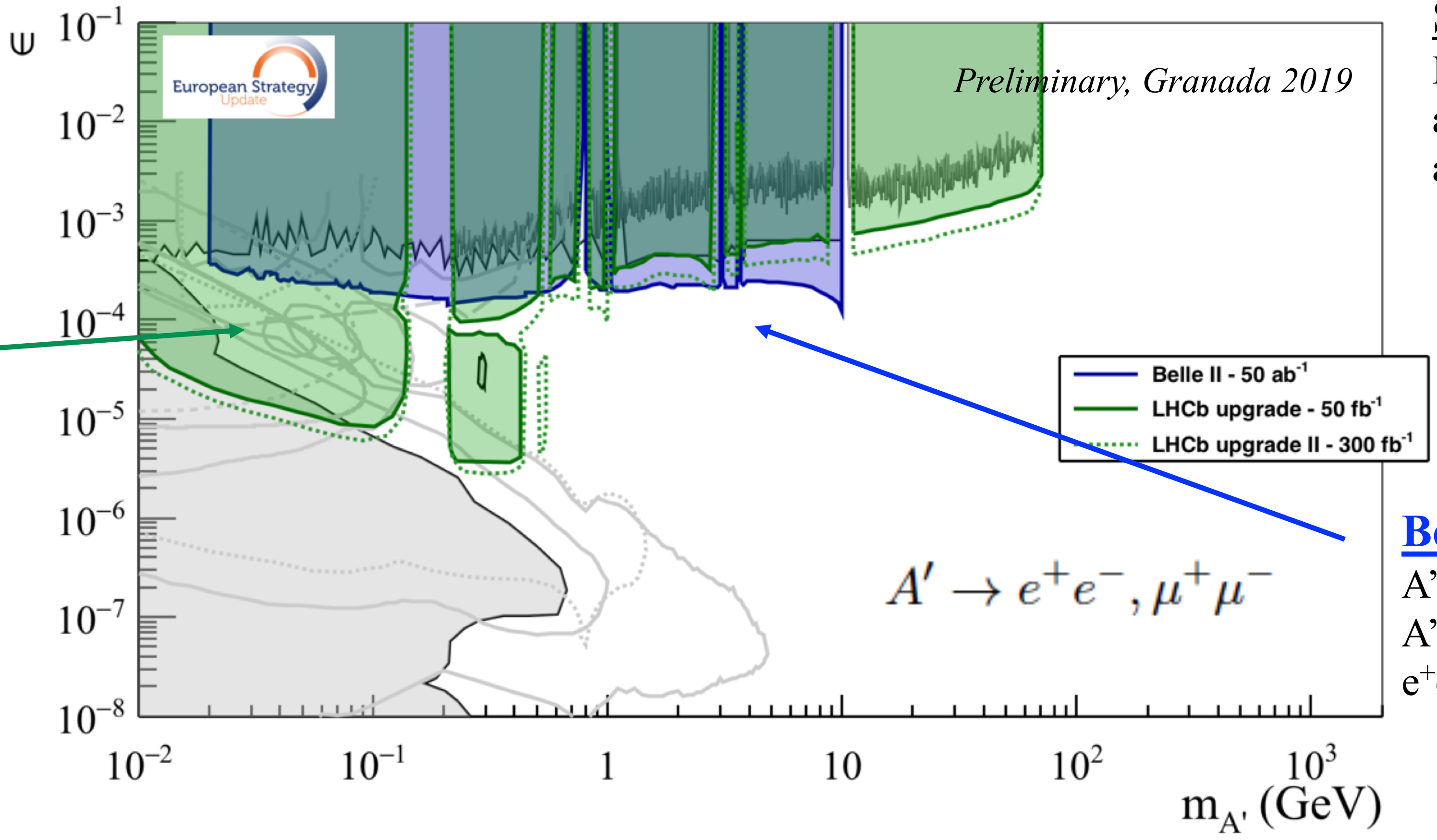
Beam dump experiments can explore very low couplings in very low mass range

Vector Portal: Dark Photon coupled to SM particles

Prospects for LHCb-upgrade (50 fb^{-1}), LHCb upgrade-II (300 fb^{-1}), Belle-II (50 ab^{-1})

LHCb – two regimes:

- $M(A') < 2\,m(\mu)$:
  $D^{*0} \longrightarrow D^0\ e^+ e^-$
  (prompt and displaced)
- $M(A') > 2\,m(\mu)$:
  Drell-Yan process
  $p\,p \longrightarrow A' \longrightarrow \mu^+\mu^-$
  (prompt and displaced)



Source:
Beyond the SM Physics
at the HL-LHC and HE-LHC
arXiv:1812.07831

Belle-II:
$A' \longrightarrow e^+e^-, \mu^+\mu^-$ where
A' is produced in the process
$e^+e^- \longrightarrow A'\,\gamma$ (radiative return)

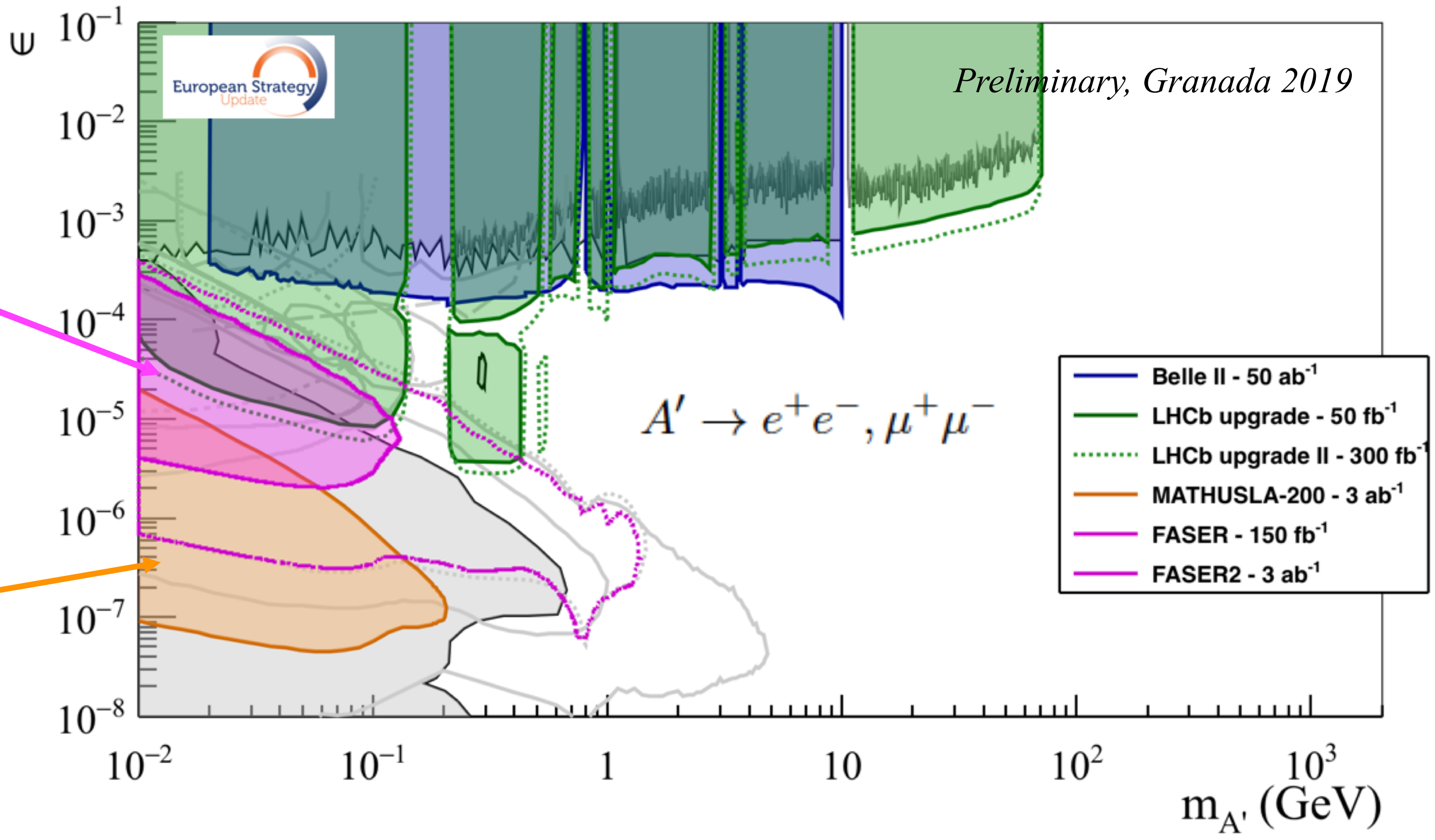
LHCb can inprove in the low-mass region thanks to the software trigger during upgrade-I.
No large improvement expected during upgrade-II

Vector Portal: Dark Photon coupled to SM particles

Prospects for MATHUSLA-200 (3 ab^{-1}), FASER (150 fb^{-1}) and FASER2 (3 ab^{-1})

FASER (150 fb^{-1}) and FASER2 (3 ab^{-1}):
Light dark photons are mainly produced through decays of light mesons, $\pi,\eta \longrightarrow \gamma A'$
$A' \longrightarrow \mu^+\mu^-$ and $e^+ e^-$

MATHUSLA-200 does not improve wrt old beam-dump experiments.



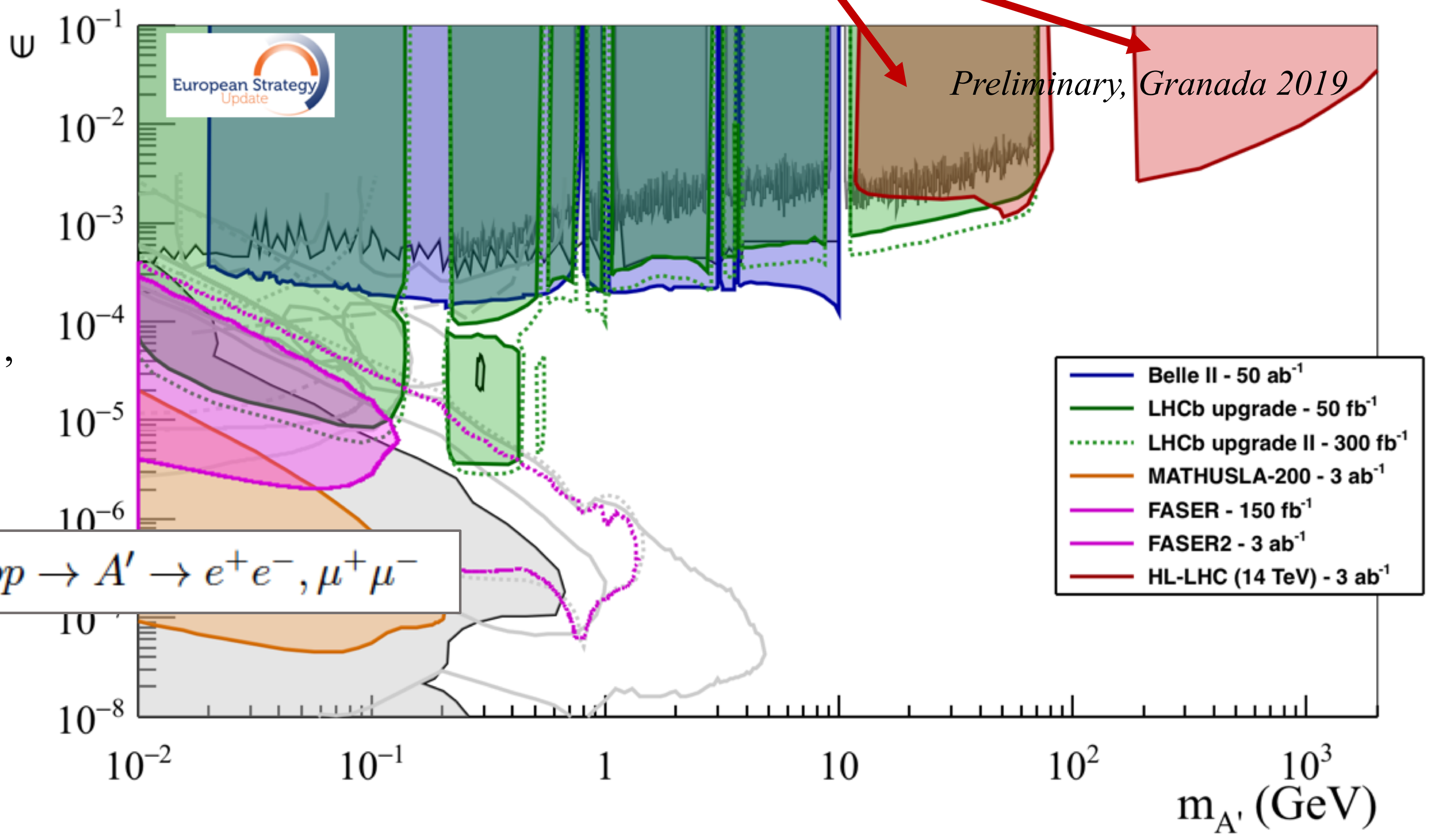
Sources:
- FASER Physics Case: arXiv:1811.12522
- Physics Beyond Colliders BSM report, arXiv:1901.09966

FASER2 can cover very low coupling range in the low-mass region.
No improvement expected from MATHUSLA.

Vector Portal: Dark Photon coupled to SM particles

Prospects for HL-LHC (14 TeV, 3 ab^{-1})

HL-LHC has also relevant projections for the non-minimal Dark Photon Model. (arXiv:1812.07831, Sect. 3.4.2)



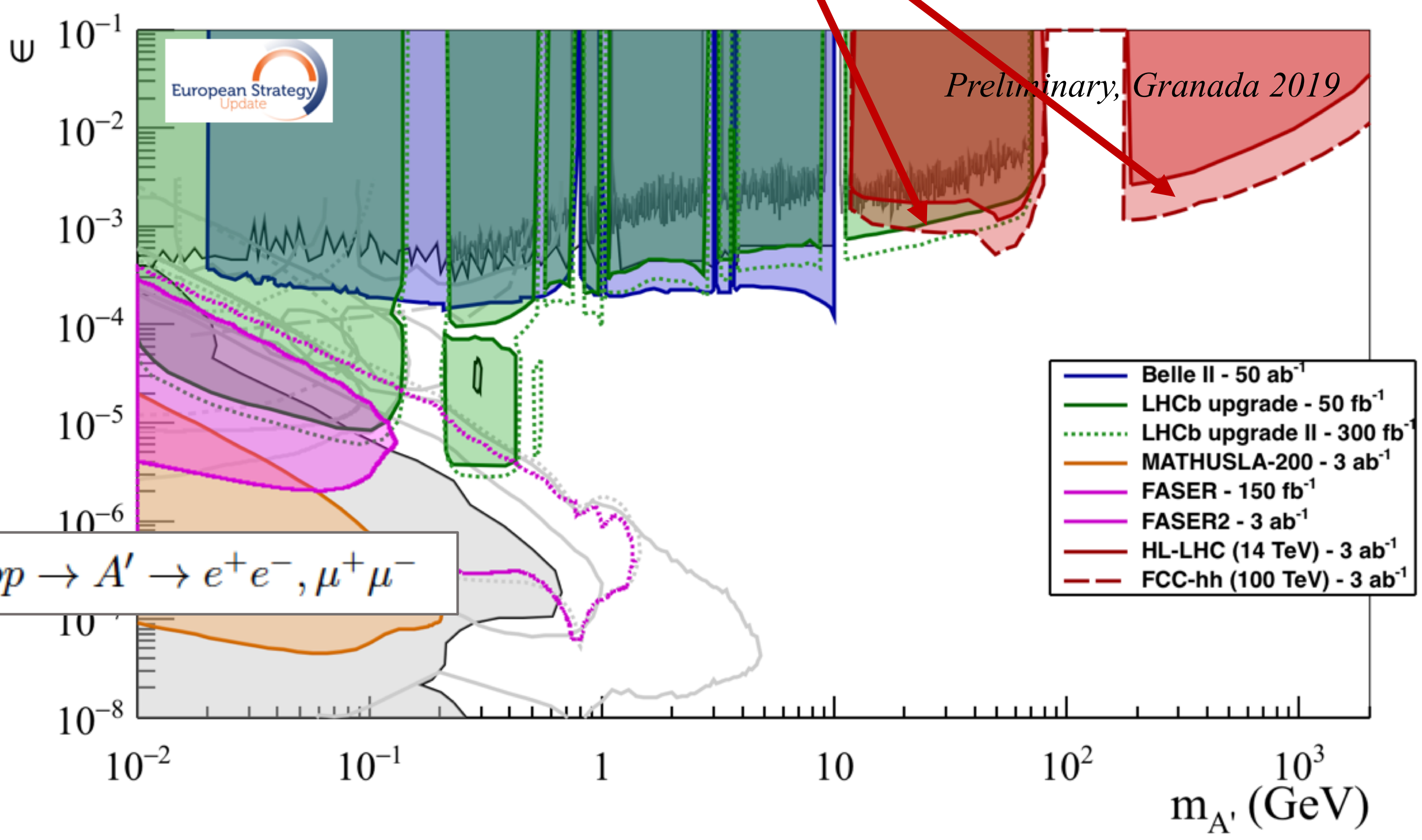
Drell-Yan production: $pp \to A' \to e^+e^-, \mu^+\mu^-$

Source:
HL-LHC physics group, based on D. Curtin et al., arXiv: 1412.0018

HL-LHC can extend the coverage in the "large" couplings, high-mass region

Vector Portal: Dark Photon coupled to SM particles

Prospects for FCC-hh (100 TeV, 3 ab^{-1})



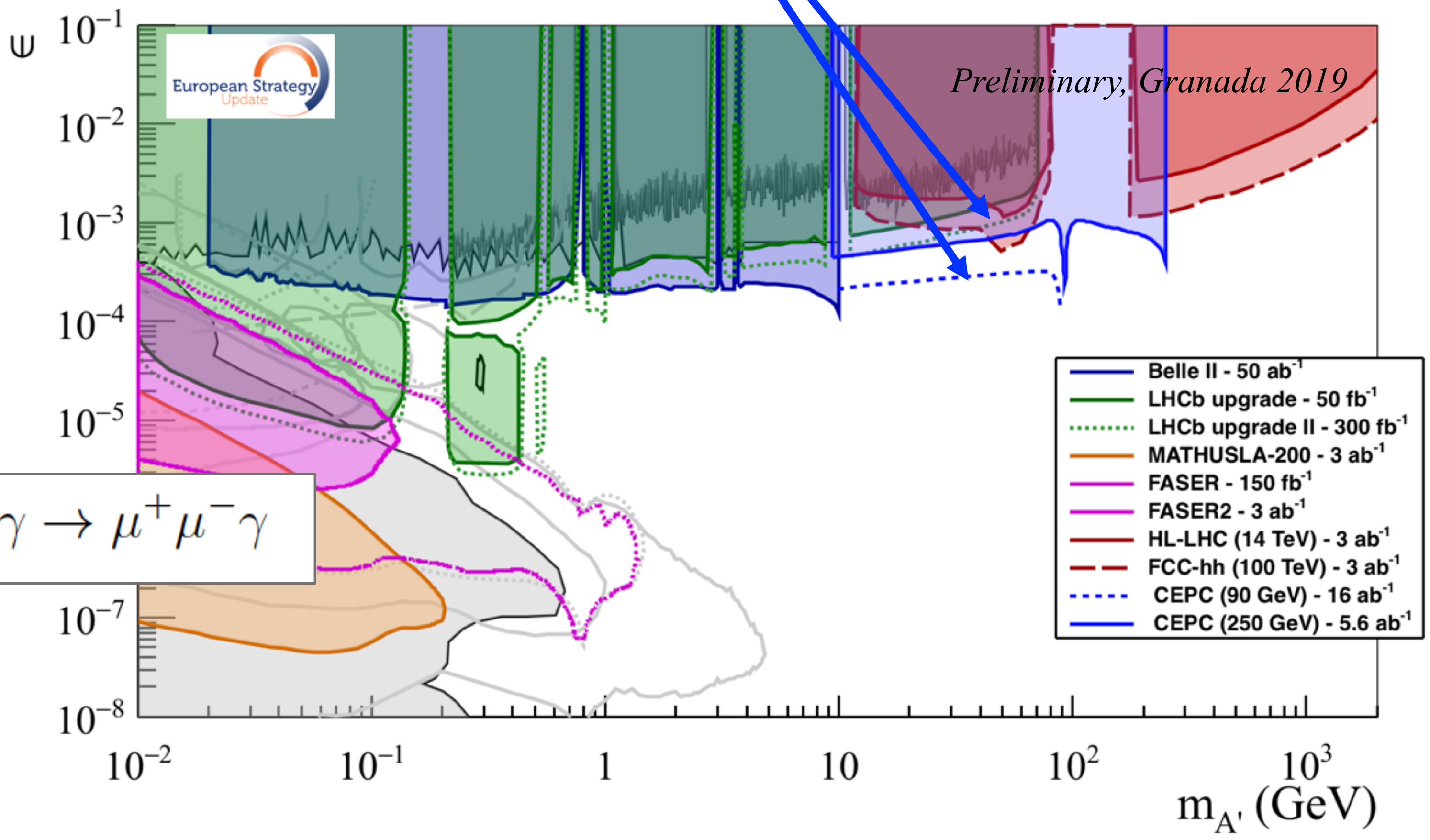
Drell-Yan production: $pp \to A' \to e^+e^-, \mu^+\mu^-$

Source:
FCC-hh physics group, based on D. Curtin et al., arXiv: 1412.0018

FCC-hh can further explore the "large" couplings, high-mass region

Vector Portal: Dark Photon coupled to SM particles

Prospects for CEPC (90 GeV, 16 ab^{-1} and 250 GeV, 5.6 ab^{-1})



$$e^+e^- \to A'\gamma \to \mu^+\mu^-\gamma$$

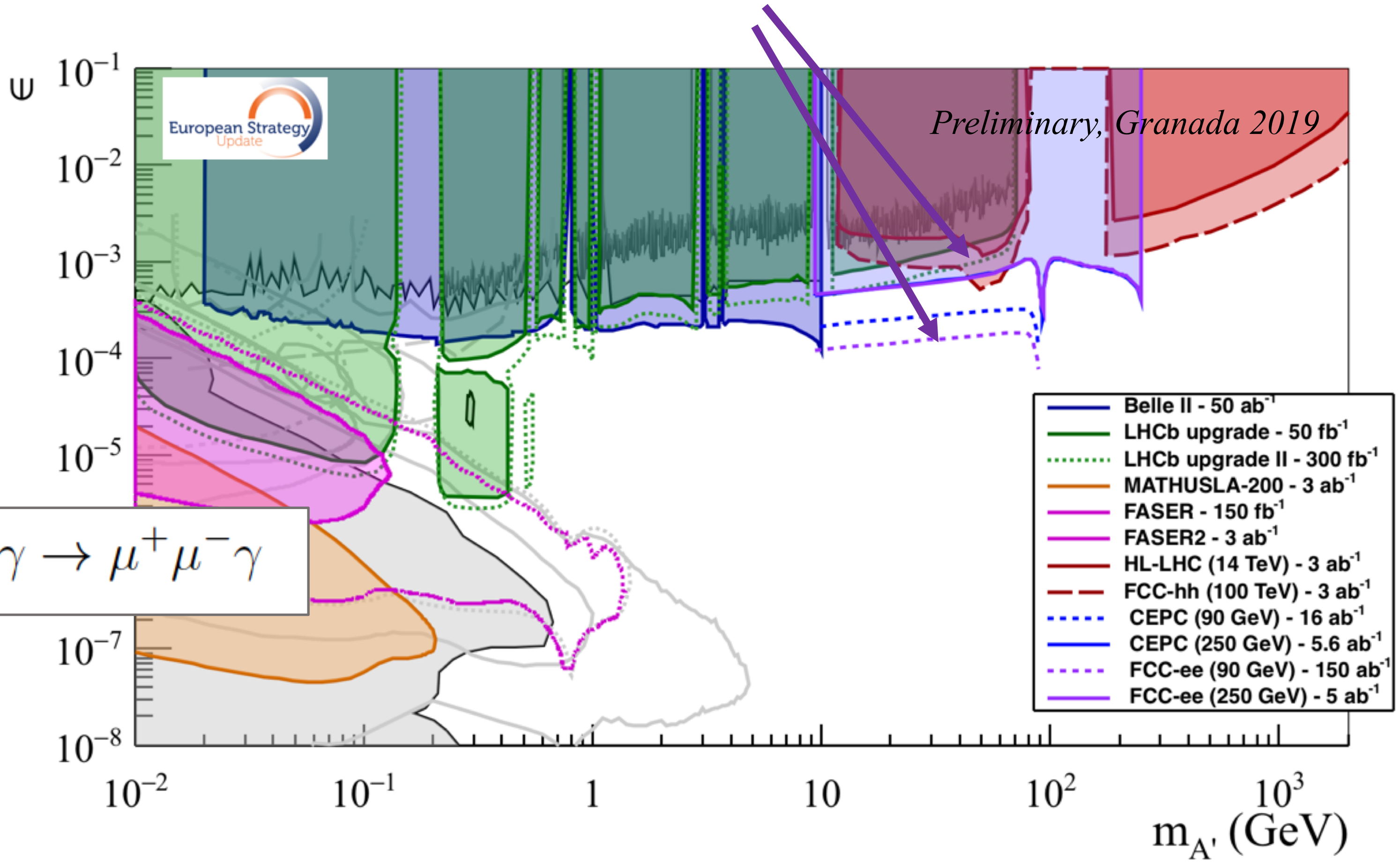
Source:
The CEPC Conceptual Design Report, Vol II: Physics and Detector, arXiv: 1811.10545, Sec. 2.3.3

Rescaling applied:
90 GeV: 0.5 ab^{-1} → 16 ab^{-1}
250 GeV: 5 ab^{-1} → 5.6 ab^{-1}

A powerful technique for all e+ e- colliders is the radiative return.
Best performance at the high luminosity at √s = 90 GeV.

Vector Portal: Dark Photon coupled to SM particles

Prospects for FCC-ee (90 GeV, 150 ab^{-1} and 250 GeV, 5 ab^{-1})



$$e^+e^- \rightarrow A'\gamma \rightarrow \mu^+\mu^-\gamma$$

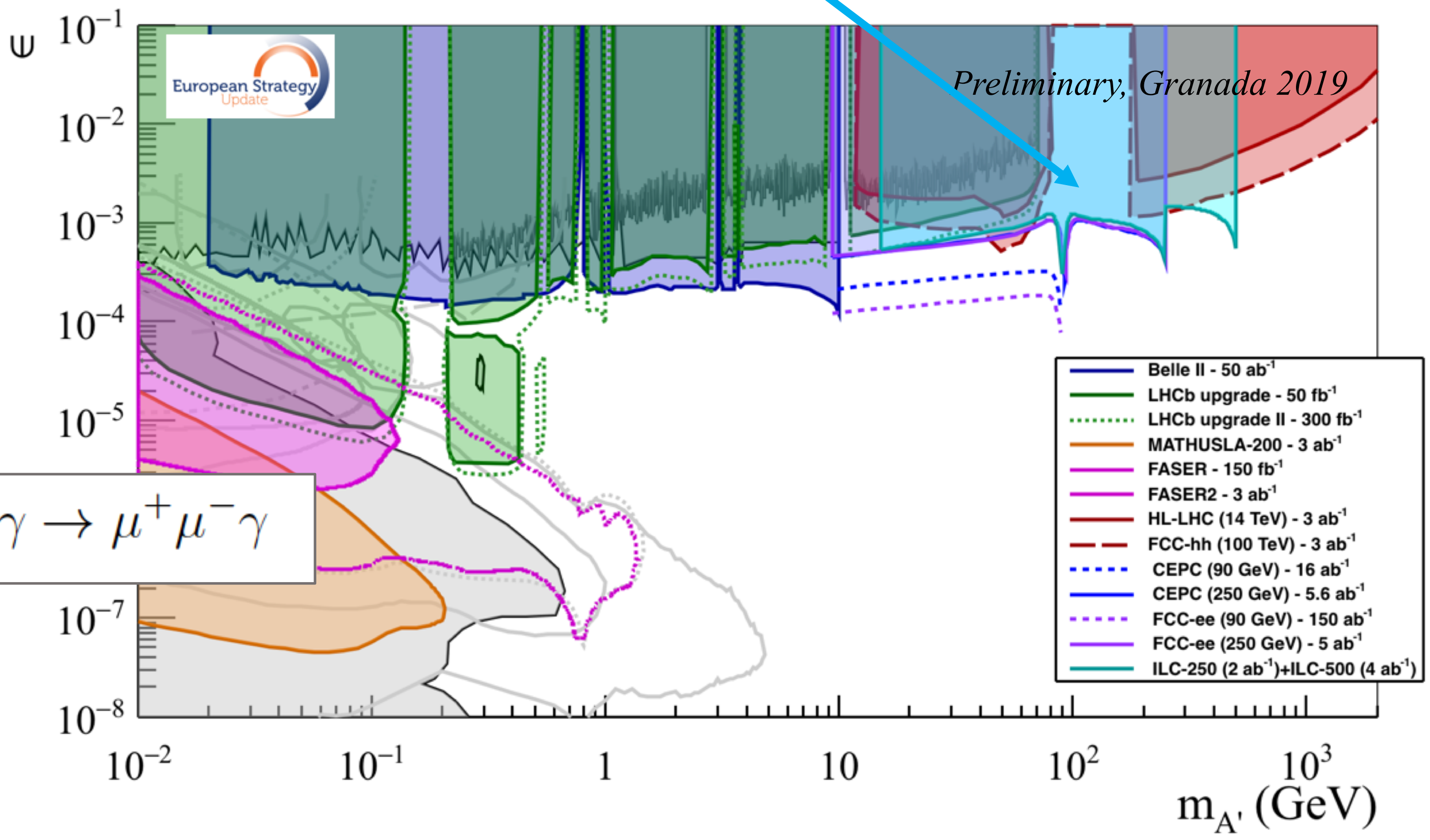
Source: Rosner et al., arXiv: 1503.07209

Rescaling applied:
90 GeV: 50 ab-1 → 150 ab-1
250 GeV: 10 ab-1 → 5 ab-1

A powerful technique for all e+ e- colliders is the radiative return.
Best performance at the high luminosity at √s = 90 GeV.

Vector Portal: Dark Photon coupled to SM particles

Prospects for ILC (250 GeV, 2 ab^{-1} and 500 GeV, 4 ab^{-1})



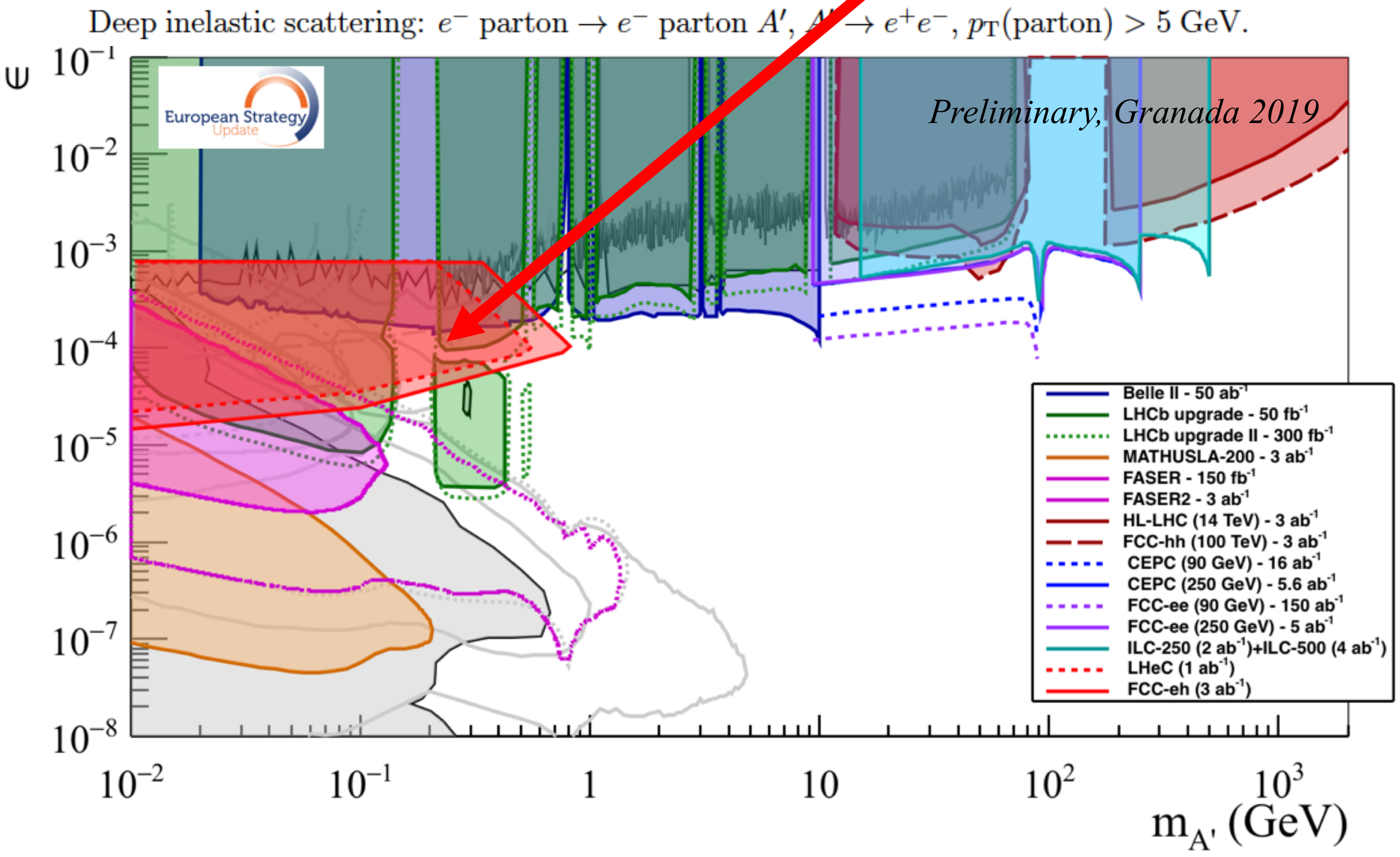
$$e^+e^- \to A'\gamma \to \mu^+\mu^-\gamma$$

Source:
M. Peskin for the ILC physics groups.

A powerful technique for all e+ e- colliders is the radiative return.
Best performance at the high luminosity at √s = 90 GeV.

Vector Portal: Dark Photon coupled to SM particles

Prospects for LHeC (1 ab^{-1}) and FCC-eh (3 ab^{-1})

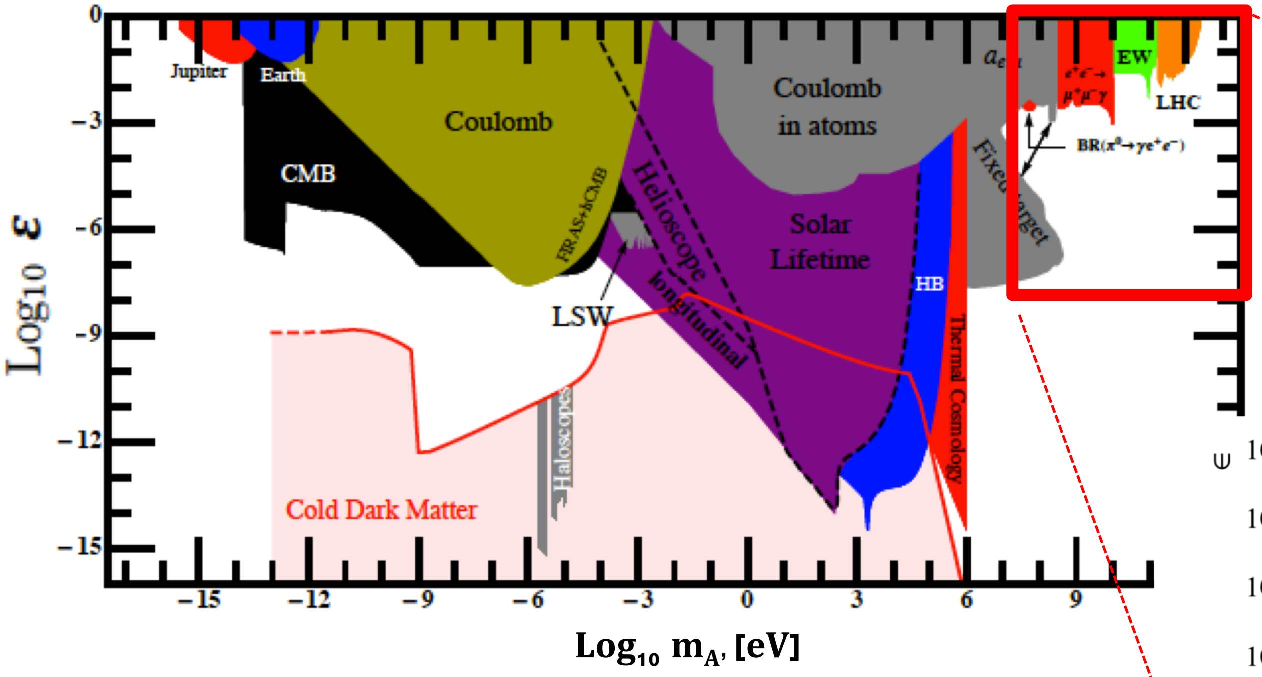


Source:

O. Fischer for the LHeC/FCC-eh physics groups.

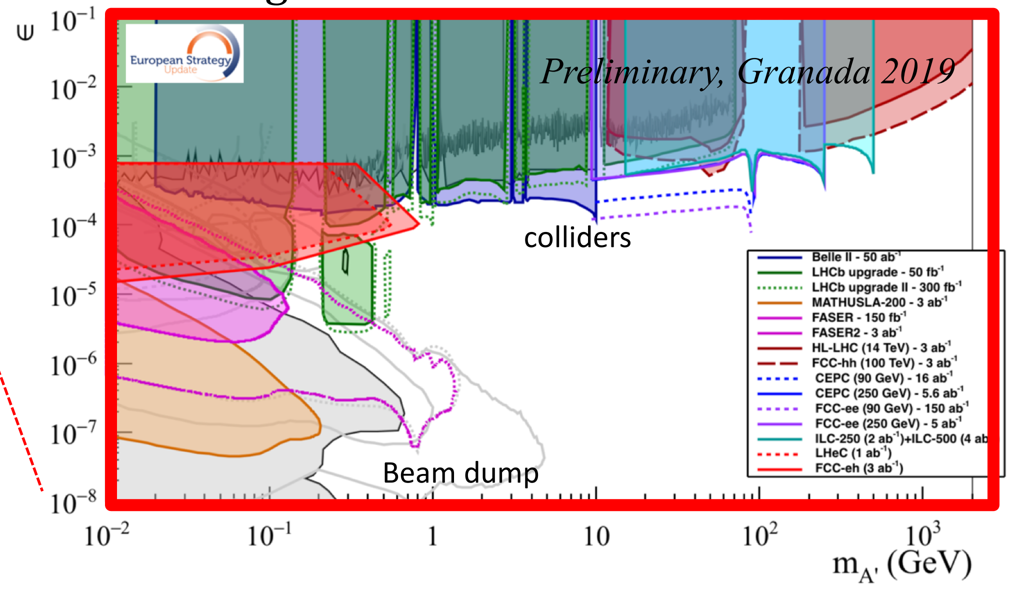
ep colliders can close the gap between prompt and displaced decays in the low mass range

Vector portal: current limits in the ℇ versus Dark Photon mass plane



MeV-TeV range accelerators' domain (range compatible with the hypothesis of DM as thermal relic)

All together



Improvements by several orders of magnitude both in low-mass low-coupling regime (beam-dump) and in high-mass large-coupling regime (colliders).

Nice complementarity between beam-dump and colliders' experiments

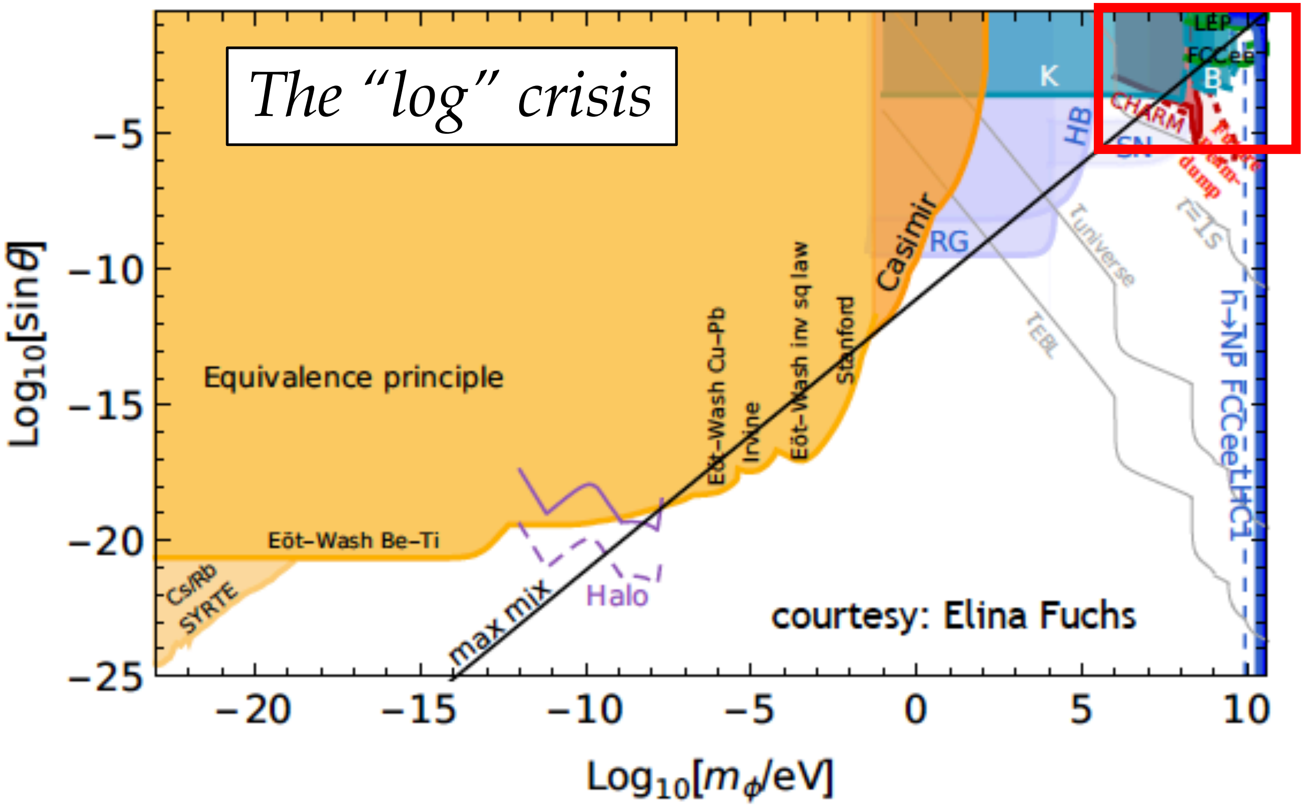
Scalar portal
(Dark Scalar/relaxion)

$$(\mu S + \lambda\, S^2) H^\dagger H$$

Wilczek, Patt, Schabinger, Wells, No, Ramsey-Musolf, Walker, Khoze, Ro, Choi, Englert, Zerwas, Lebedev, Mambrini, Lee, Everett, Djouadi, Falkowski, Zupan, Tytgat, Gunion, Dawson, Perez, Frugiuele, Fuchs, Schlaffer, Altmannshofer, Batell, Bezrukov, Bondarenko, Gorbunov, Boyarsky, Craig, Essig, Grojean, deNiverville, Pospelov, Krnjaic, Ruchayskiy, Strassler, Zurek,
+ many others

Scalar Portal: possible physics motivations

Relaxion: light feeble goldstone boson, with both CP-even and CP-odd couplings with the Higgs, may stabilize the Higgs mass against radiative corrections and provide baryogenesis.
Generic light scalar could also be light mediator between SM and LDM, in case of secluded annihilation.



MeV-100 GeV range is accessible at accelerators' based experiments

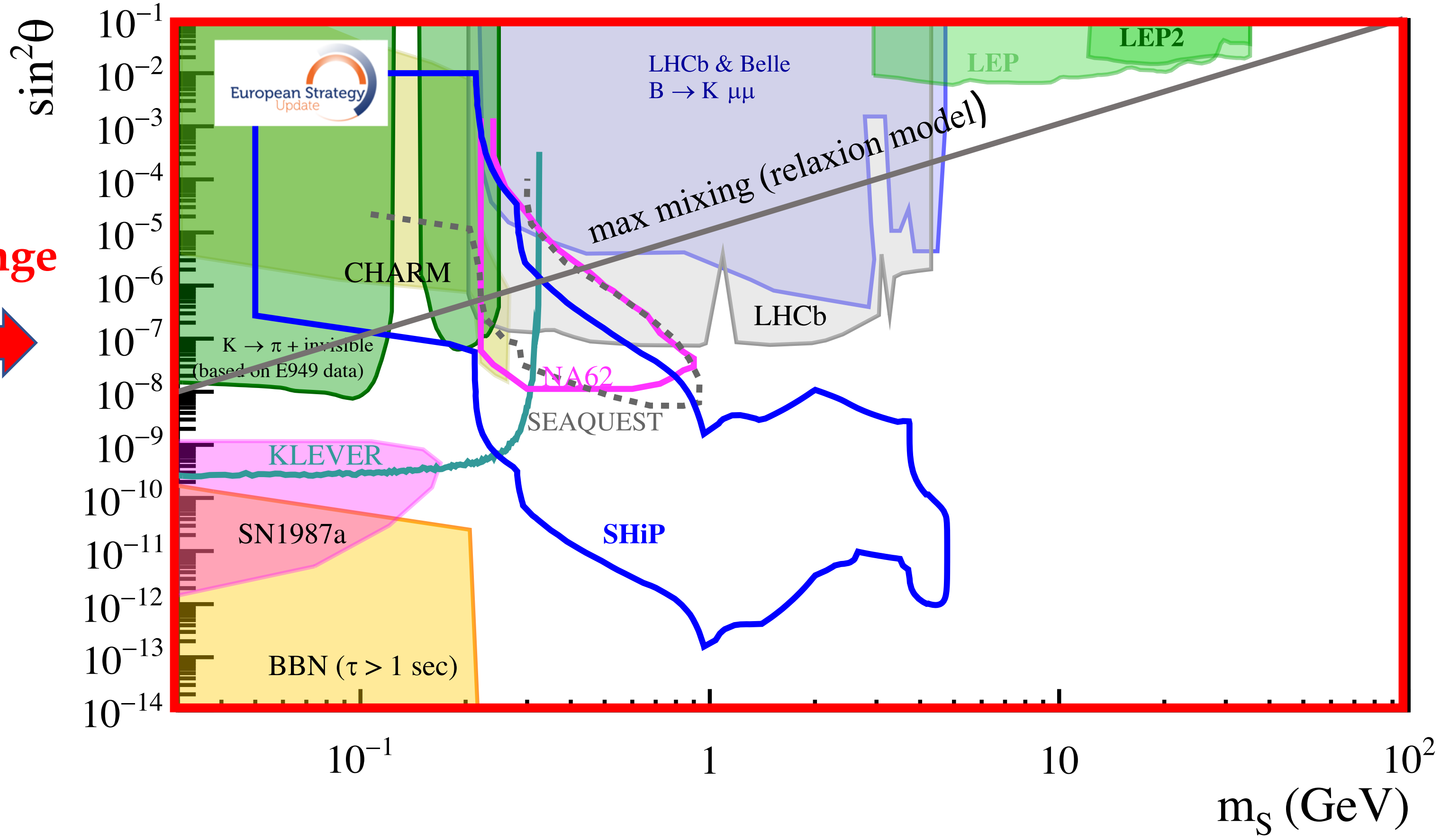
See Perez's talk

No scale associated.
We need a multi-scale (multi-experiment) approach.

Scalar Portal: "generic" dark scalar

Existing limits and projections for future beam dump and fixed target experiments.

Zoom in the MeV-100 GeV range



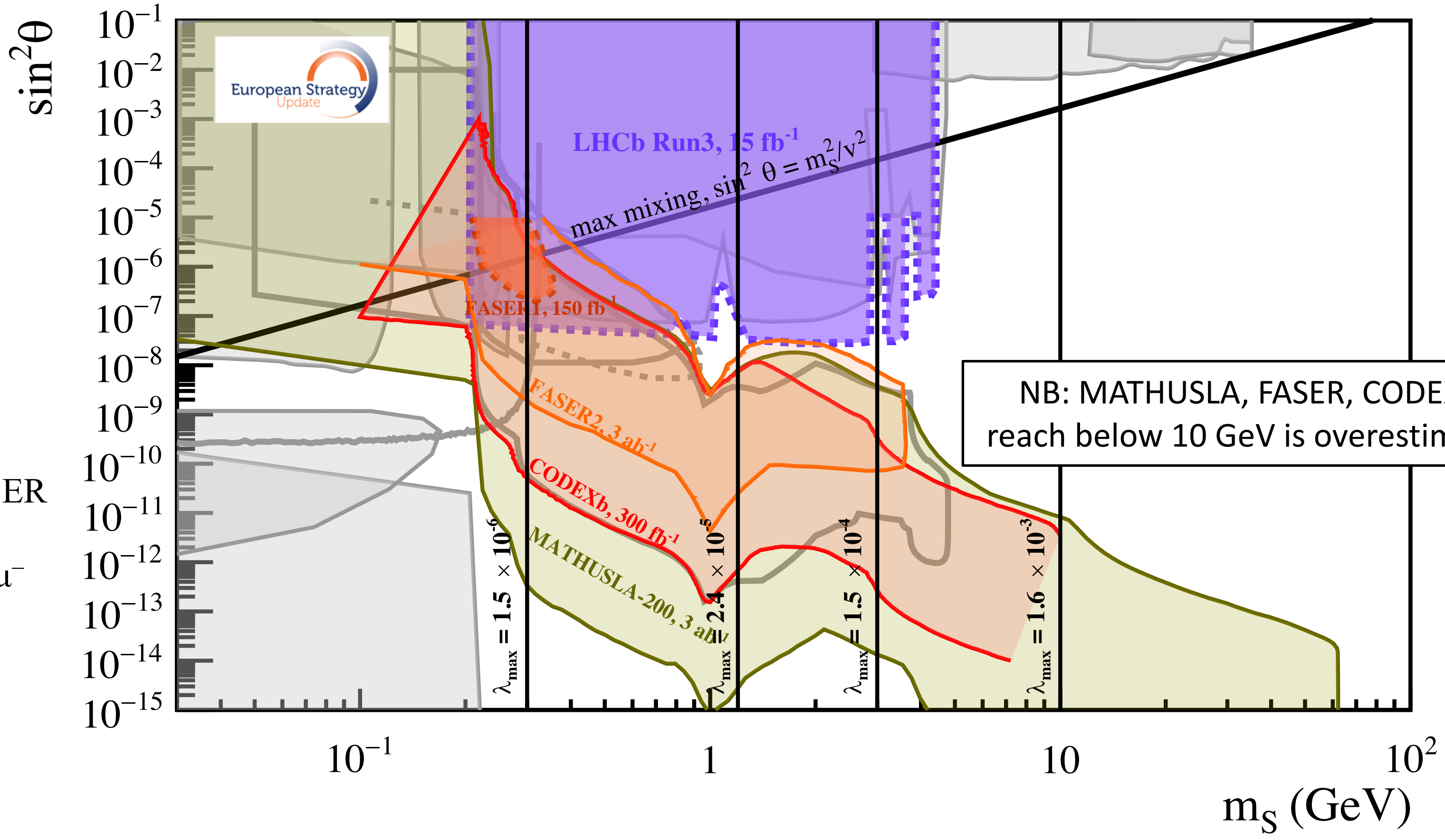
Source:
Physics Beyond Colliders BSM report, arXiv:1901.09966.

See Vallee and Graverini's talks

SHiP and other beam-dump/fixed target experiments will probe a large mass region below 5 GeV

Scalar Portal: Dark Scalar

Projections for MATHUSLA, FASER, CODEX-b, LHCb….



Source:
Physics Beyond Colliders BSM report, arXiv:1901.09966.

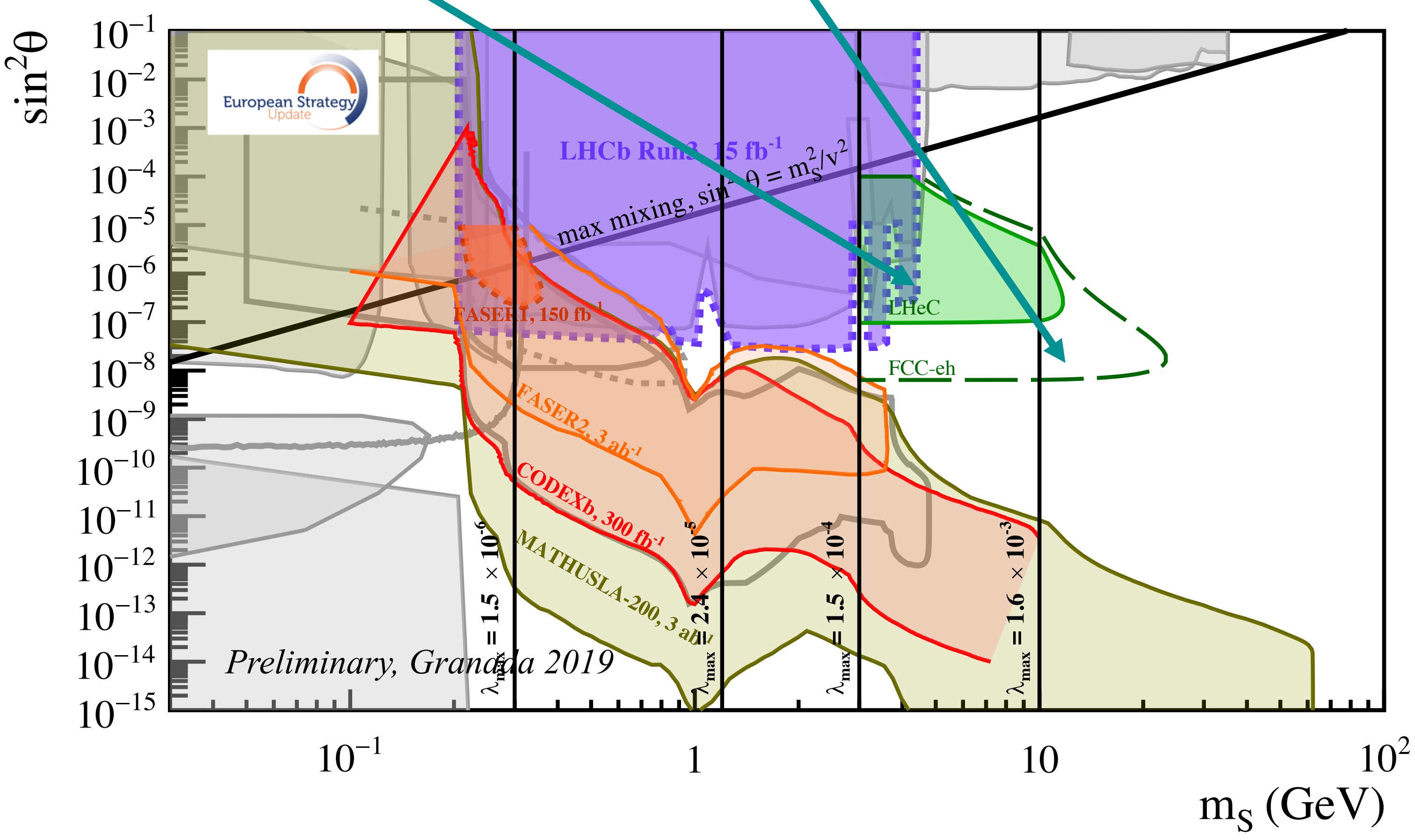
NB: MATHUSLA, FASER, CODEX-b reach below 10 GeV is overestimated

Production processes:
MATHUSLA, CODEX, FASER
$H \longrightarrow SS$;
LHCb: $B \longrightarrow K \; H^* \longrightarrow K \mu^+\mu^-$

MATHUSLA, FASER, CODEX can explore a large fraction of parameter space in the low-couplings regime.
NB:Current projections assume a (unnatural) high value for λ (λ=4x10^{-3}) for m_S<10 GeV.

Scalar Portal: Dark Scalar

Projections for LHeC (1 ab^{-1}) and FCC-eh (3 ab^{-1}) - (fixed λ=4x10^{-3}).



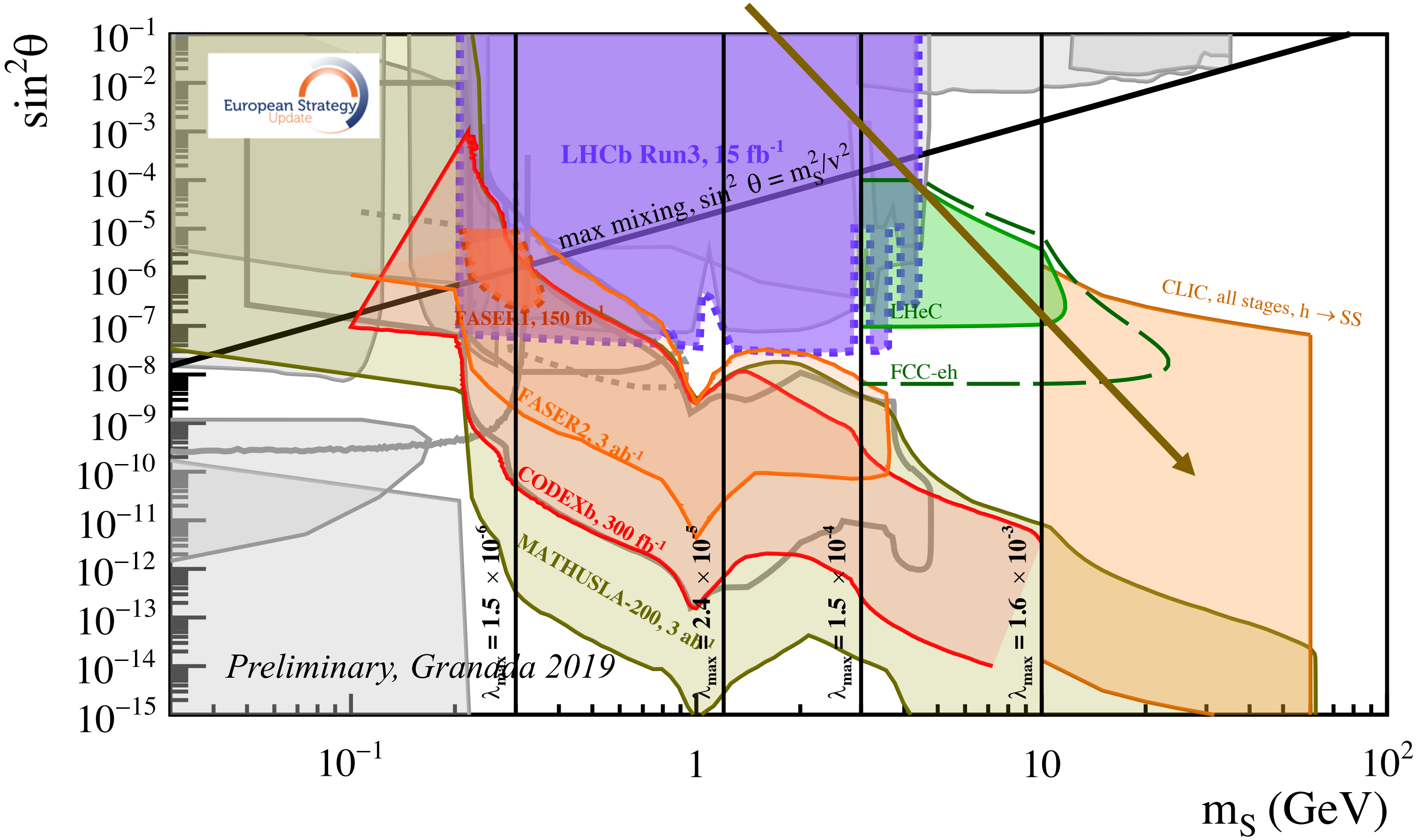
Source:
The LHeC/FCC-eh physics groups (O. Fischer et al.)

Method:
Higgs ⟶ SS
S ⟶ visible decays
(assuming fixed λ = 4x10^{-3})

LHeC and FCC-eh can extend the reach beyond LHCb.

Scalar Portal: Dark Scalar

Projections for CLIC: 380 GeV (0.5 ab^{-1}), 1500 GeV (1.5 ab^{-1}), 3000 GeV (3.0 ab^{-1})



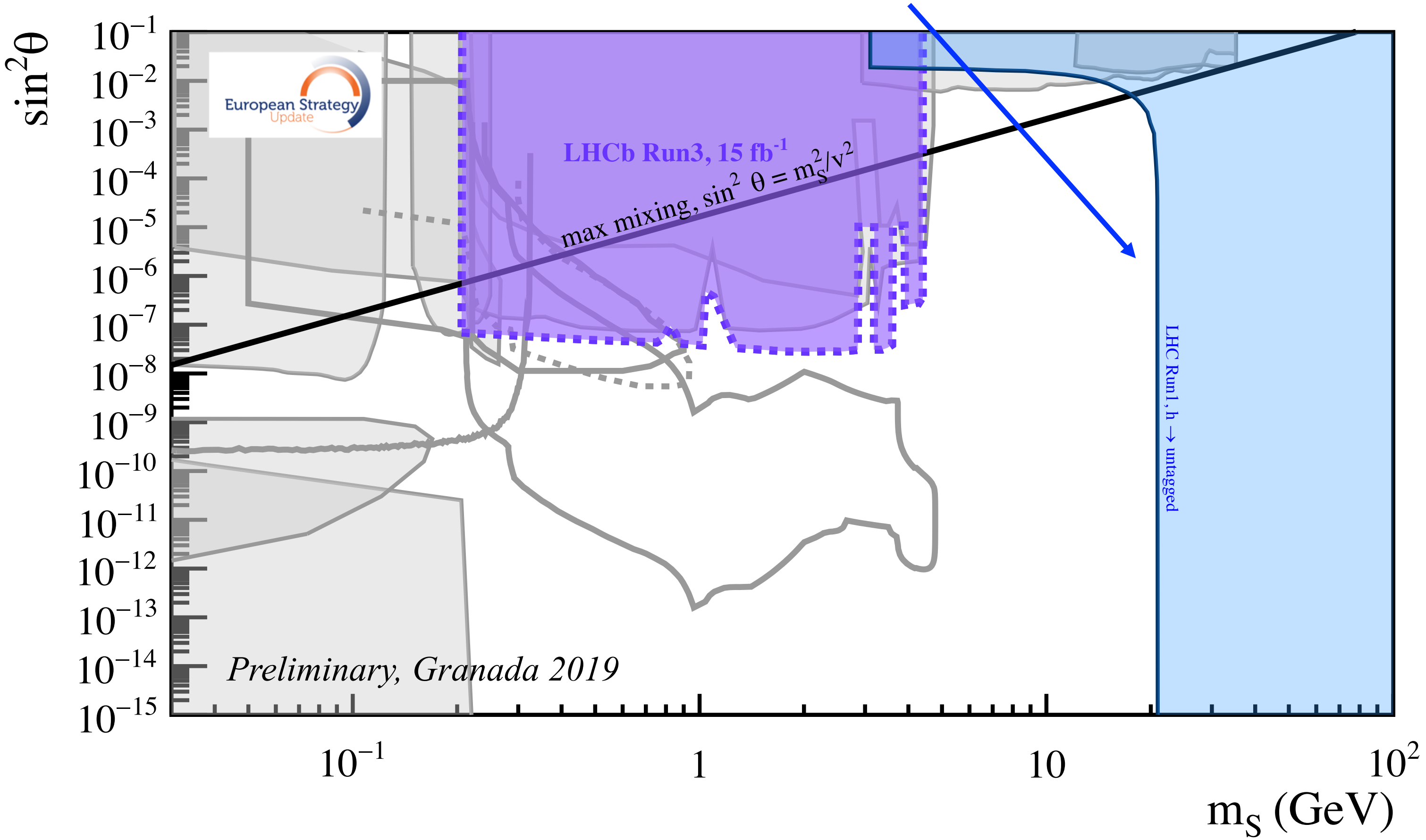
Source:
R. Franceschini for the CLIC physics groups.

Method:
Higgs ⟶ SS
S ⟶ visible decays
(assuming fixed $\lambda = 4\text{x}10^{-3}$)

CLIC (summing up all stages) covers mass range 10-60 GeV and low couplings.

Scalar Portal: Dark Scalar

Current limits from LHC Run 1



Source:
Fuchs, Schlaffer, Perez,
update from 1807.10842
Γ_h(NP) from 1403.1582

Method
Indirect limits from fit of Higgs width and Higgs BRs (model dependent)

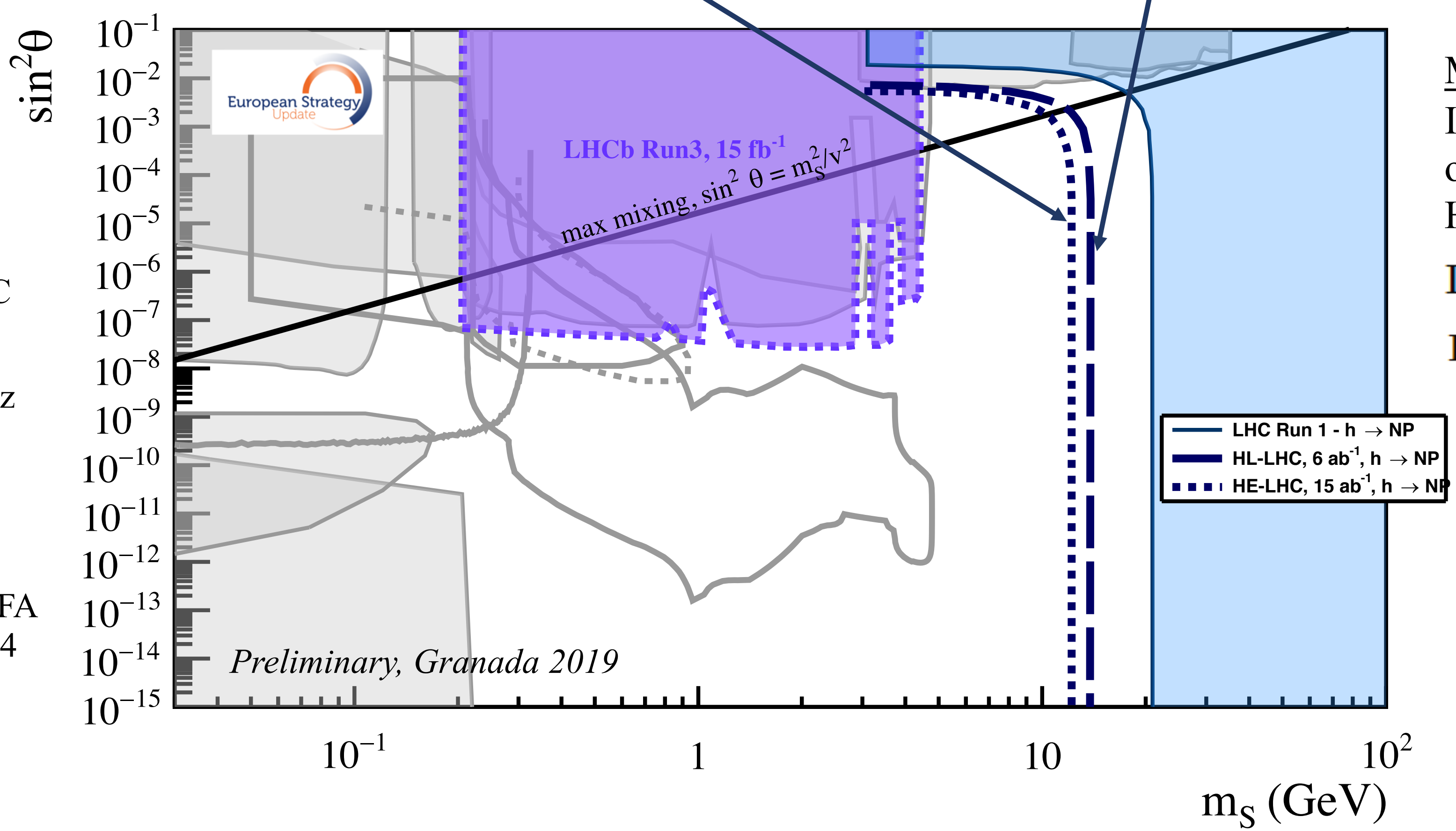
$$\Gamma_h^{tot} = \cos^2\theta\, \Gamma_h^{tot,SM} + \Gamma_h^{NP}$$

$$\Gamma_h^{NP} = \Gamma(h \to \phi\phi)$$

Fit of the Higgs couplings is very powerful in constraining very low $\sin^2\theta$ values in the "high" (> 10 GeV) mass regime.

Scalar Portal: Dark Scalar

Projections for HE-LHC, 15 ab^{-1} and HL-LHC, 6 ab^{-1}



<u>Source:</u>
Beyond the SM Physics at the HL-LHC and HE-LHC arXiv:1812.07831,

Fit by Fuchs, Schlaffer, Perez based on 1807.10842 and Γ_h(NP) from preliminary ECFA fit results (see spares)

To be updated with final ECFA fit results - arXiv:1905.03764

<u>Method</u>
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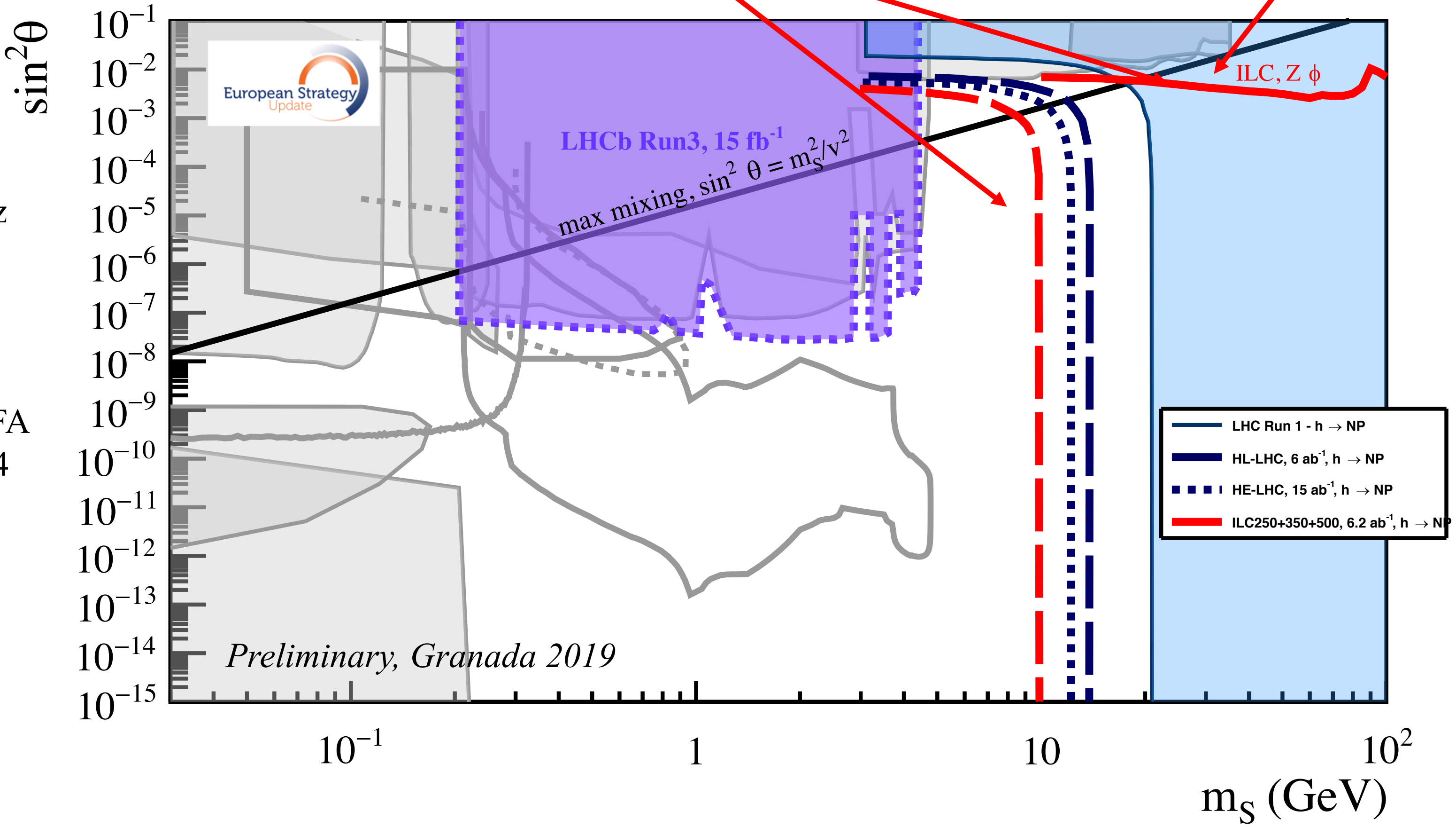
Scalar Portal: Dark Scalar

Projections for ILC: 240 GeV, 2 ab^{-1}

All backgrounds included



Source:
Fit by Fuchs, Schlaffer, Perez based on 1807.10842 and Γ_h(NP) from preliminary ECFA fit results (see spares)

To be updated with final ECFA fit results - arXiv:1905.03764

Methods:
1) Indirect limits from fit of Higgs width and Higgs BRs (model dependent)

$$\Gamma_h^{tot} = \cos^2\theta\,\Gamma_h^{tot,SM} + \Gamma_h^{NP}$$

$$\Gamma_h^{NP} = \Gamma(h \to \phi\phi)$$

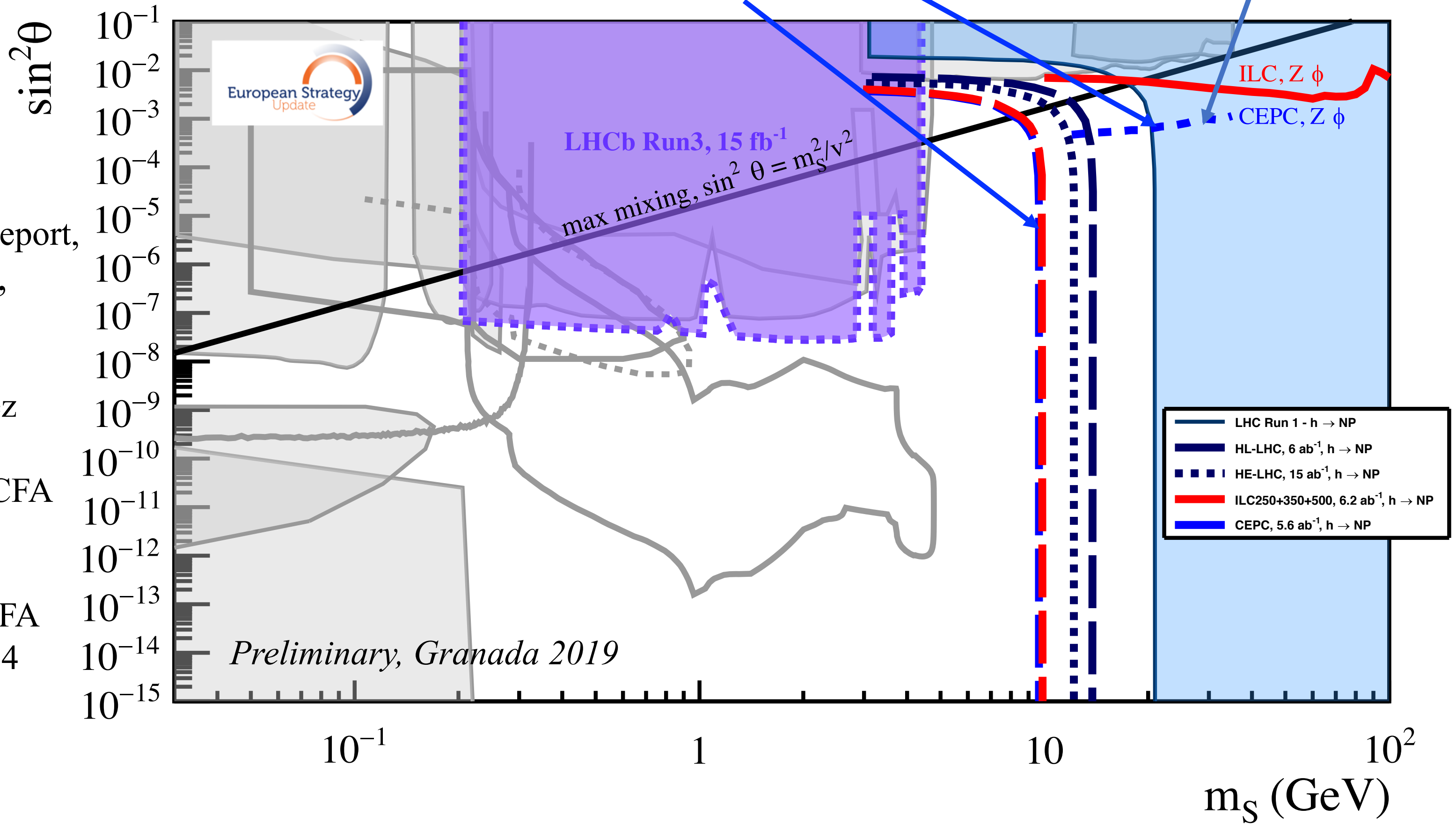
2) $e^+ e^- \longrightarrow Z\,\phi$ (recoil)

Beyond the fit of the Higgs couplings, the recoil technique is very powerful for e+ e- machines. Beam polarization can help in reducing the backgrounds.

Scalar Portal: Dark Scalar

Projections for CEPC, 250 GeV, 5 ab^{-1}

Simple scaling
from LEP1 results



<u>Source:</u>
CEPC Conceptual Design Report, Vol II: Physics and Detector, arXiv: 1811.10545.

Fit by Fuchs, Schlaffer, Perez based on 1807.10842 and Γ_h(NP) from preliminary ECFA fit results (see spares)

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<u>Methods:</u>

1) Indirect limits from fit of Higgs width and Higgs BRs (model dependent)

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Beam polarization can help in reducing the backgrounds.

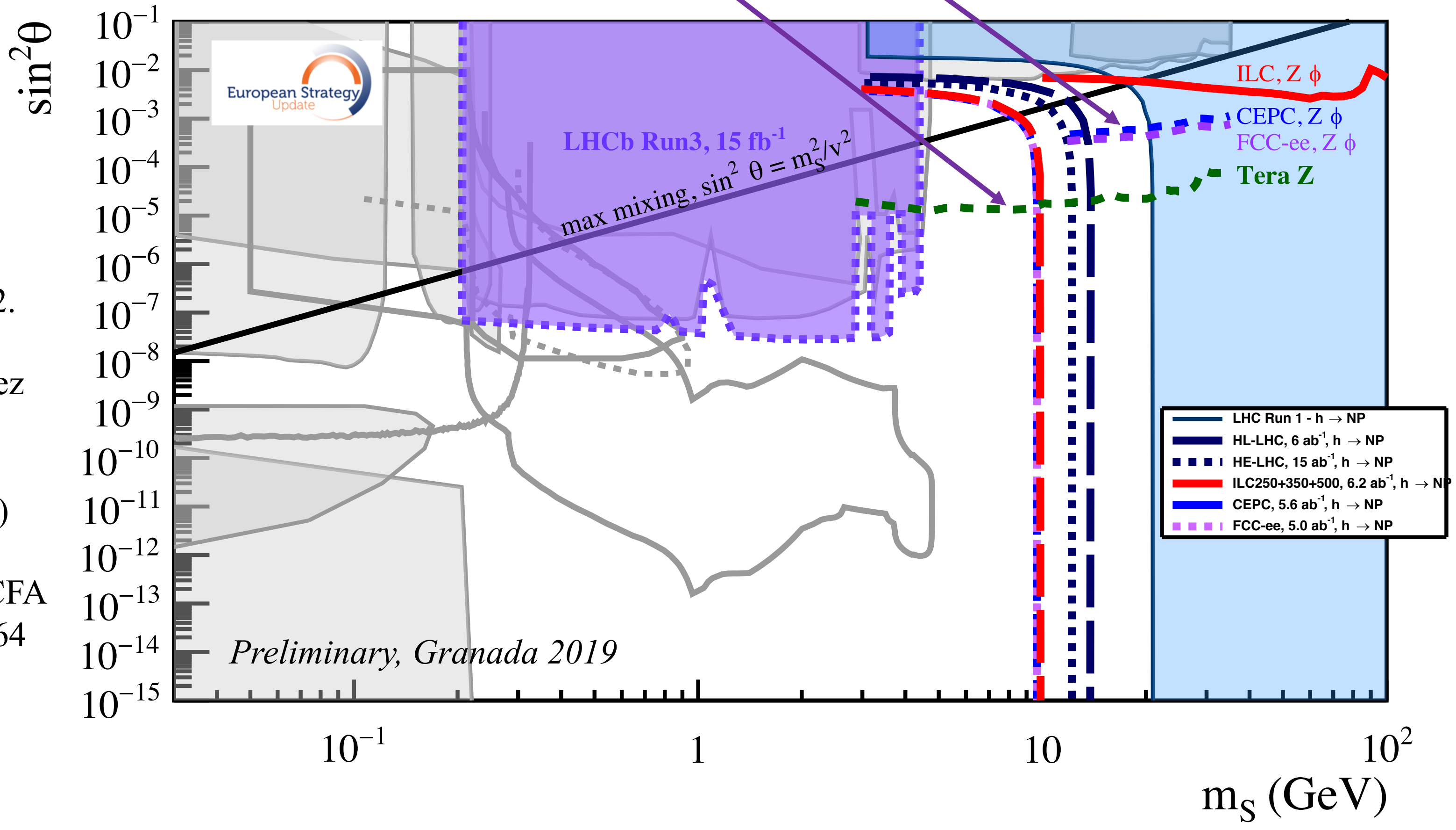
Scalar Portal: Dark Scalar

Projections for FCC-ee: 240 GeV (10 ab^{-1}) and Tera-Z option

Source:
The FCC-ee physics groups based on arXiv:1807.10842.

Fit by Fuchs, Schlaffer, Perez based on 1807.10842 and Γ_h(NP) from preliminary ECFA fit results (see spares)

To be updated with final ECFA fit results - arXiv:1905.03764



Methods:
1) Indirect limits from fit of Higgs width and Higgs BRs (model dependent)

$$\Gamma_h^{tot} = \cos^2\theta\,\Gamma_h^{tot,SM} + \Gamma_h^{NP}$$

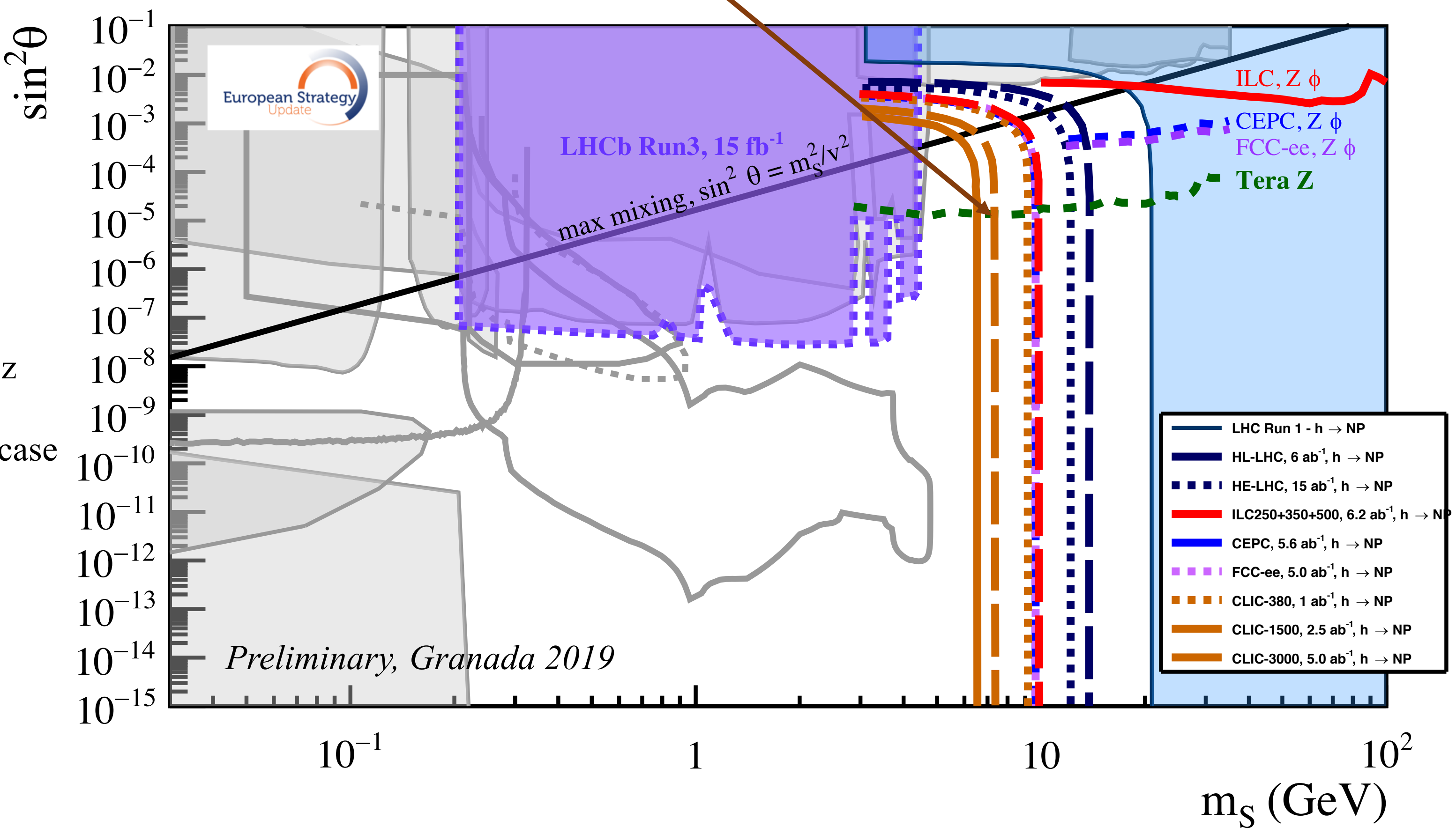
$$\Gamma_h^{NP} = \Gamma(h \to \phi\phi)$$

2) $e^+ e^- \longrightarrow Z\,\phi$ (recoil)
3) $Z \longrightarrow \phi\, l^+ l^-$ (Z-pole)

ILC, CEPC and FCC-ee have similar performance for indirect searches.
The Tera-Z option can further push down the limit in the mass range below the Z-pole.

Scalar Portal: Dark Scalar

Projections for CLIC: 380 GeV (0.5 ab^{-1}), 1500 GeV (1.5 ab^{-1}), 3000 GeV (3.0 ab^{-1})



Source:

Elaborated from Fig.8 of The CLIC potential for NP arXiv: 1812.02093.

Fit by Fuchs, Schlaffer, Perez based on 1807.10842 and Γ_h(NP) from CLIC physics case

To be updated with final ECFA fit results – arXiv:1905.03764

Methods:

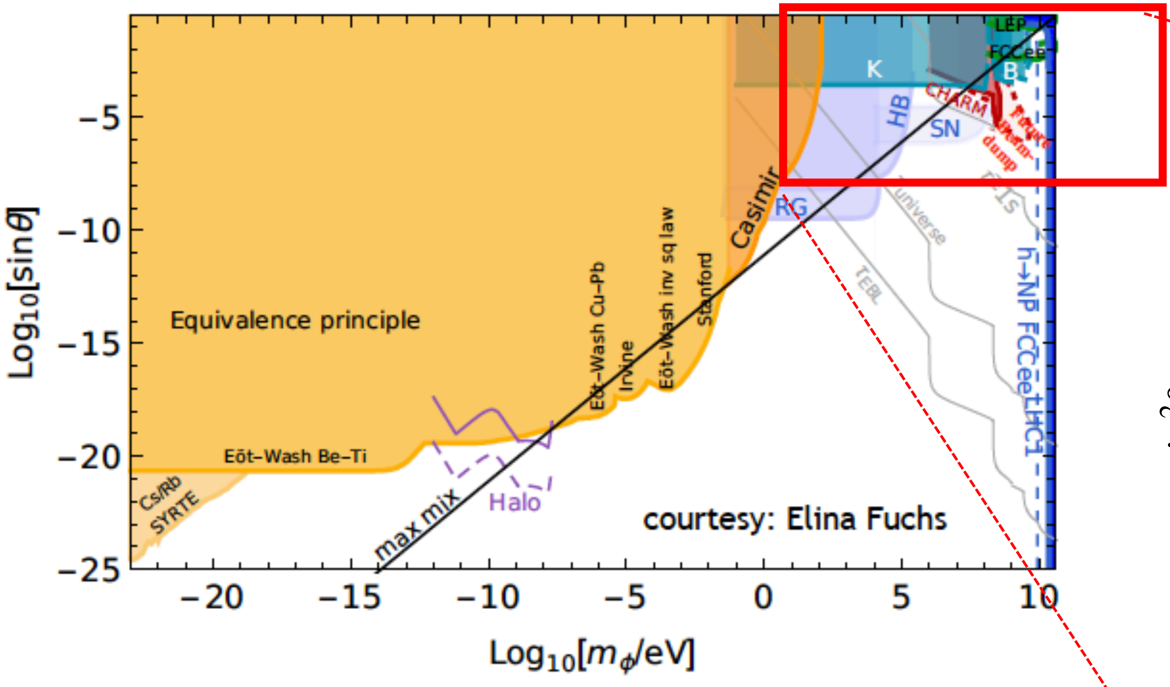
Indirect limits from fit of Higgs width and Higgs BRs (model dependent)

$$\Gamma_h^{tot} = \cos^2\theta\, \Gamma_h^{tot,SM} + \Gamma_h^{NP}$$

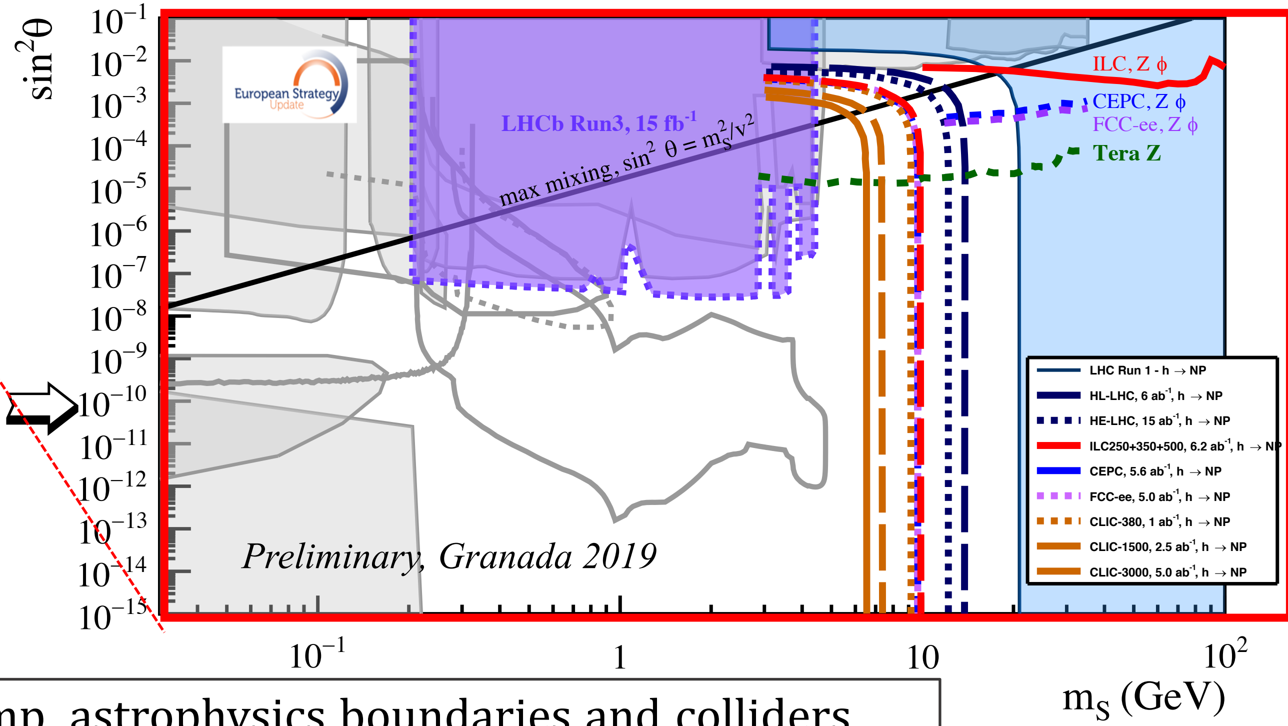
$$\Gamma_h^{NP} = \Gamma(h \to \phi\phi)$$

CLIC (summing up all stages) further constrains the relaxion model below 10 GeV.

Hunting a "heavy" relaxion/scalar-portal



MeV-100 GeV range
is accessible at accelerators' based experiments



High-mass range can be excluded by the knowledge of the Higgs couplings; Improvements by several orders of magnitude possible in low-mass low-coupling regime using direct searches.

Nice complementarity between beam-dump, astrophysics boundaries and colliders.
Together they can explore a large fraction of the "natural" relaxion region.

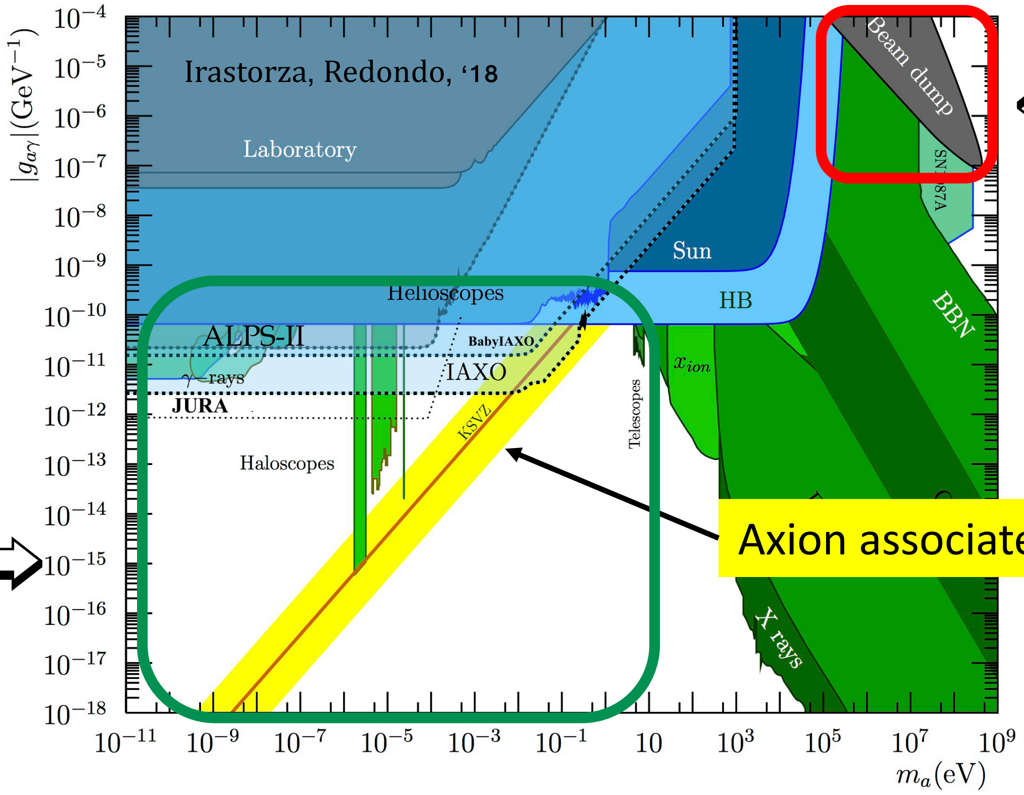
Pseudo-scalar portal
Axions/ALPs with photon couplings

$$\frac{a}{f_a} \tilde{F}_{\mu\nu} F^{\mu\nu}$$

Weinberg, Wilczek, Witten, Conlon, Arvanitaki, Dimopoulos, Dubovsky, Gavela, Soreq, Williams, Kaloper, March-Russell, Cicoli, Goodsell, Lazarides, Shafi, Choi, Peccei, Quinn, Olive, Arkani-Hamed, Harnik, Kaplan, Espinoza, Quiros, Hooper, Feng, Kahlhoefer, Bauer, Neubert, Thamm, Jaeckel
+ many others

Pseudo-Scalar portal: axions/ALPs with photon coupling

Search for axions/ALPs: extremely lively and established field, mostly in the sub-eV mass range
Need of a systematic investigation in the MeV-tens of GeV range.



Interest to explore the MeV-TeV region at accelerator-based experiments

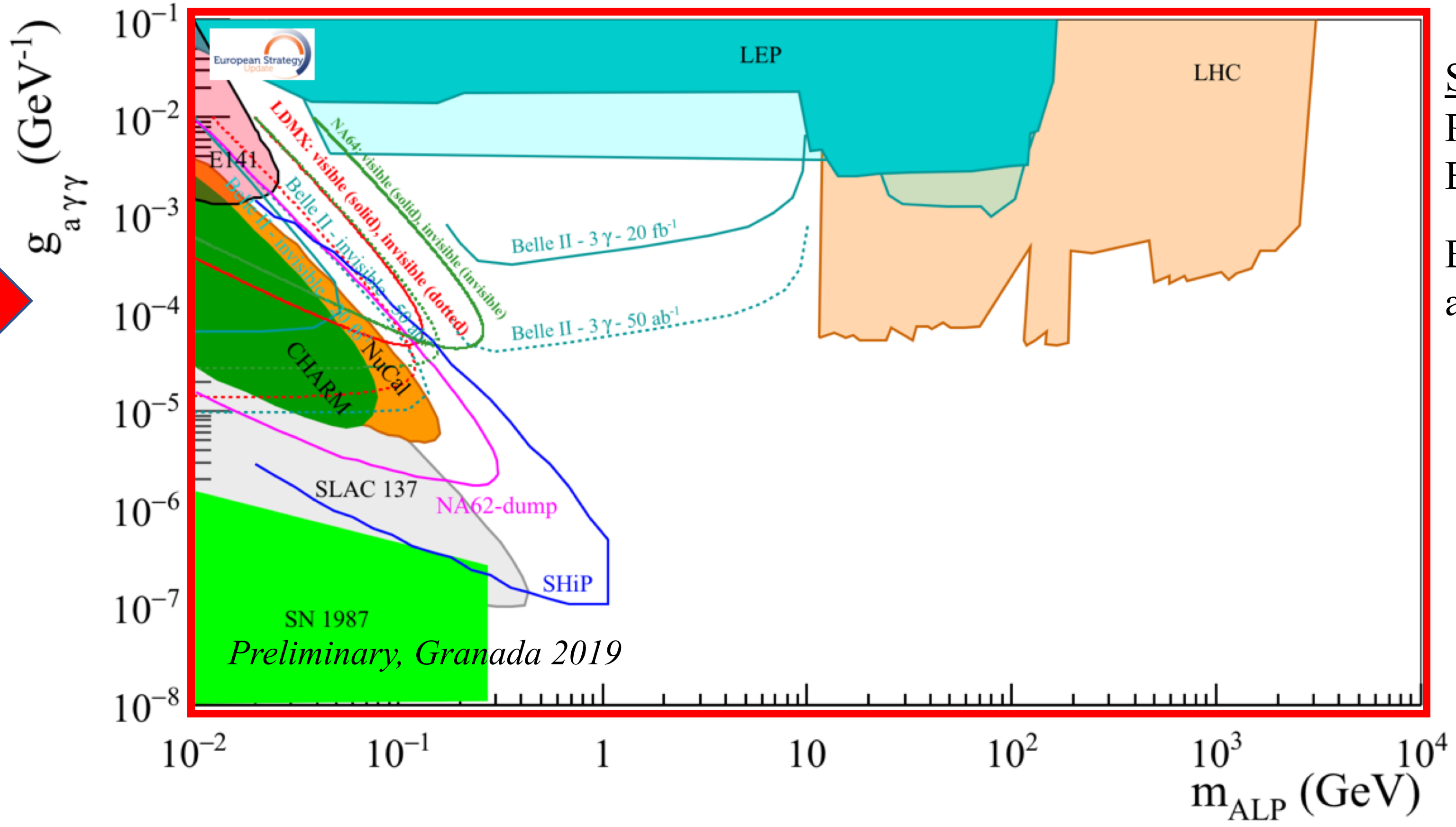
Axion associated to the Peccei-Quinn symmetry

sub-eV range accessible at helioscopes and haloscopes

Pseudo-Scalar portal: ALPs with photon coupling

Current limits, projections for beam dump experiments, **Belle II**..

Zoom in the MeV-TeV range

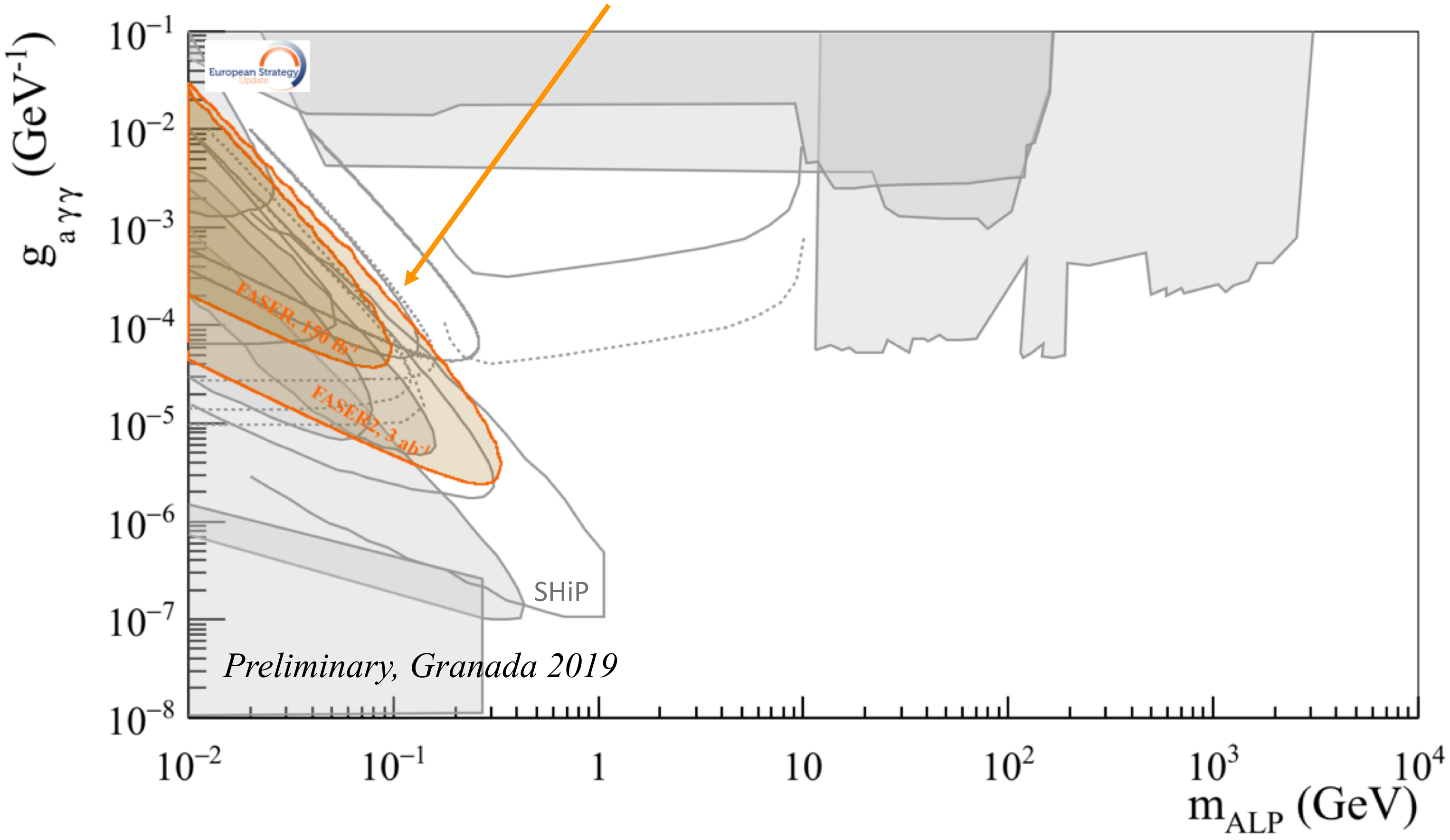


Source:
Physics Beyond Colliders BSM report, arXiv:1901.09966.

B. Gavela et al., arXiv:1811.05466

Pseudo-Scalar portal: ALPs with photon coupling

Prospects for FASER (150 fb^{-1}) and FASER2 (3 ab^{-1})

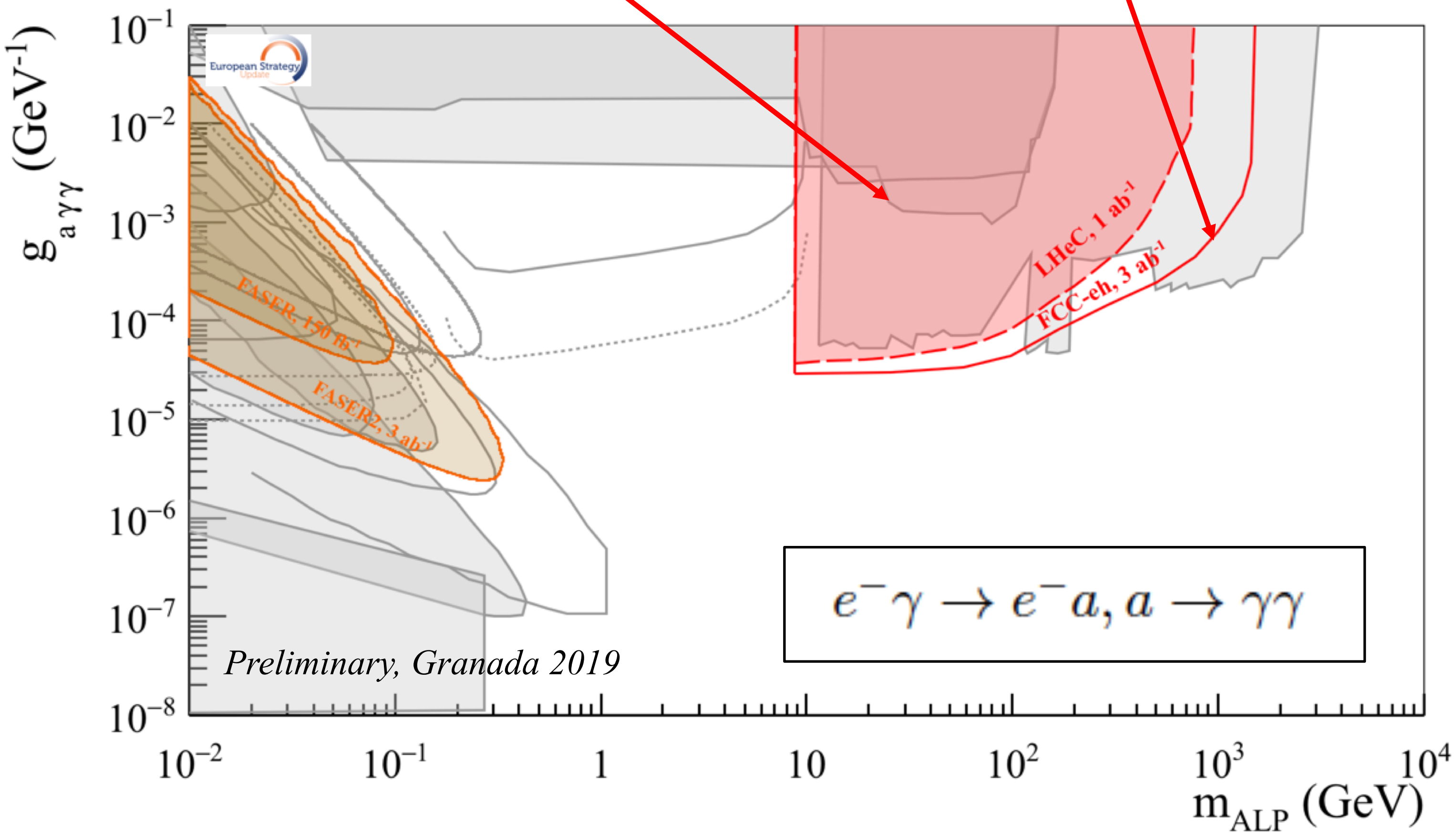


Source:
FASER Physics Case:
arXiv:1811.12522

FASER improves at low mass low-couplings, but not competitive with SHiP.

Pseudo-Scalar portal: ALPs with photon coupling

Prospects for LHeC (60 GeV e-, 7 TeV p, 1 ab^{-1}) and FCC-eh (60 GeV e-, 50 TeV p, 3 ab^{-1})

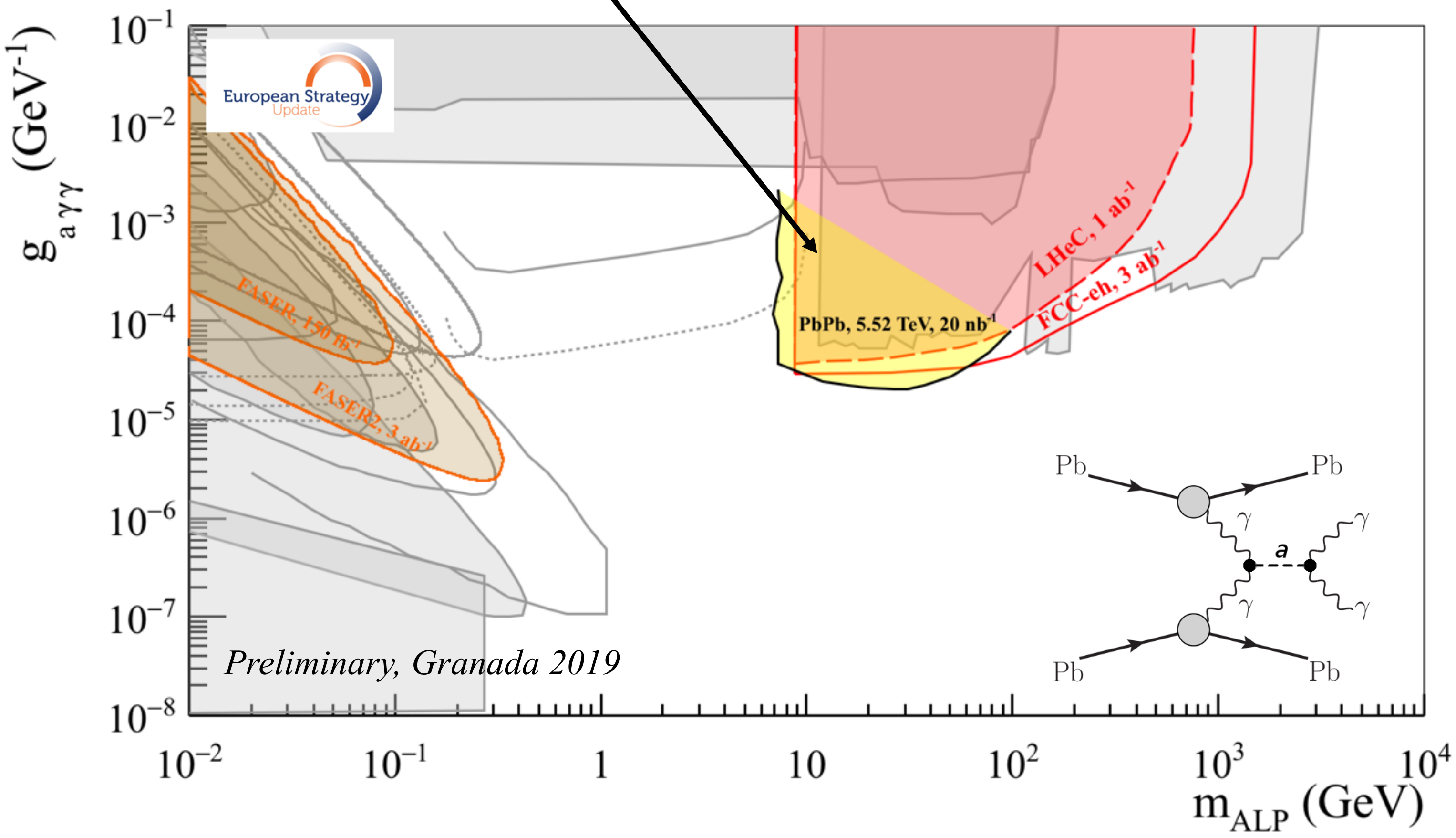


Source:
LHeC/FCC-eh physics Groups (O. Fischer et al.) based on arXiv:1904.10657

LHeC and FCC-eh improve over the current limits from the LHC above 10 GeV.

Pseudo-Scalar portal: ALPs with photon coupling

Prospects for Heavy Ions, Pb Pb (5.52 TeV, 20 nb^{-1})

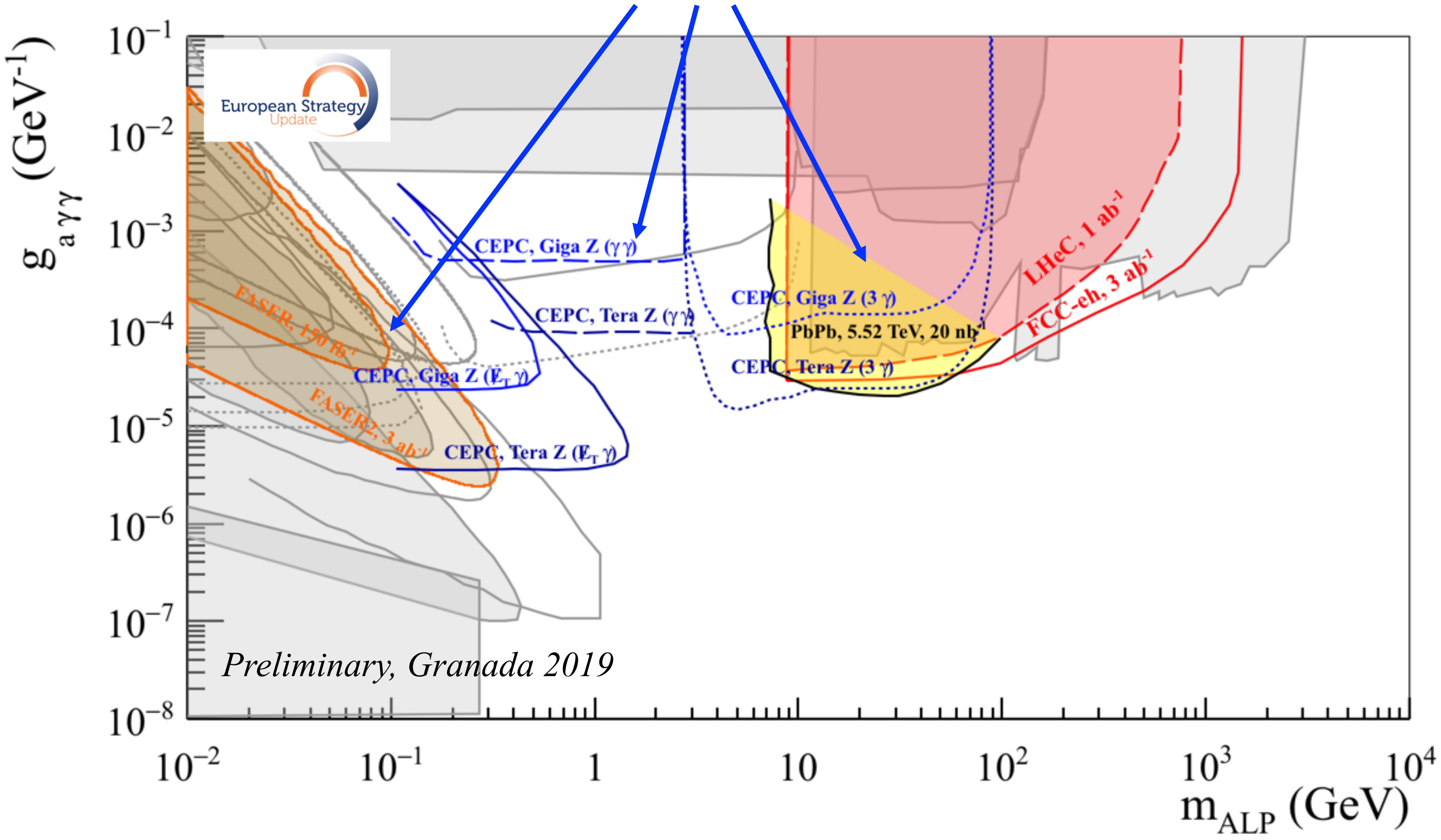


<u>Source:</u>
New Physics in Heavy Ions collisions,
ESPP input # 151 and references therein.

Heavy ions run with PbPb and 20 nb^{-1} can improve between 8 and 100 GeV

Pseudo-Scalar portal: ALPs with photon coupling

Prospects for CEPC: Giga Z and Tera Z

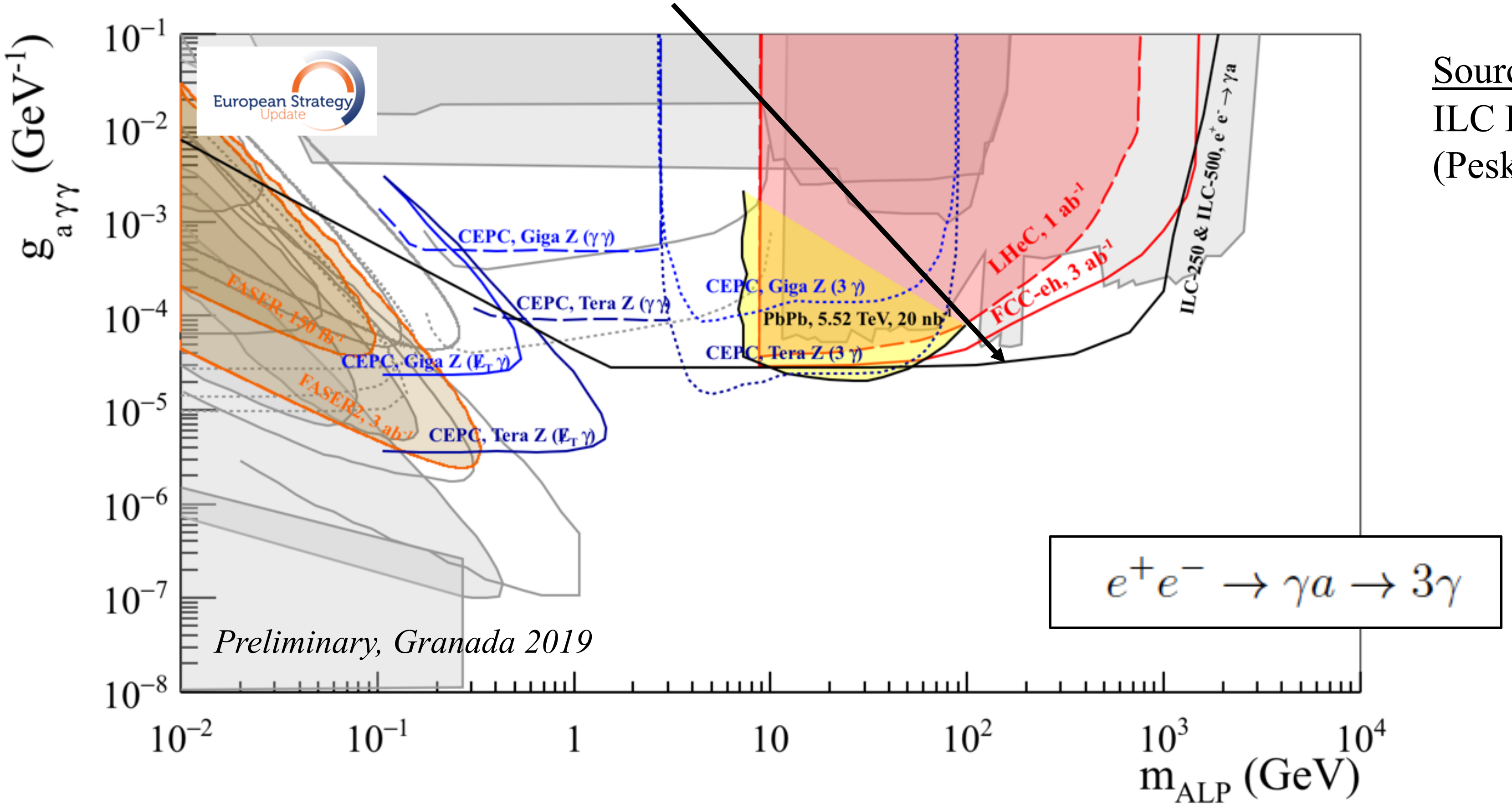


Source:
Adapted from the CEPC physics case, arXiv:1811.10545

CEPC with the Tera-Z option can improve over the whole range 100 MeV-1 TeV.

Pseudo-Scalar portal: ALPs with photon coupling

Prospects for ILC: 250 GeV (2 ab^{-1}), 500 GeV (4 ab^{-1})

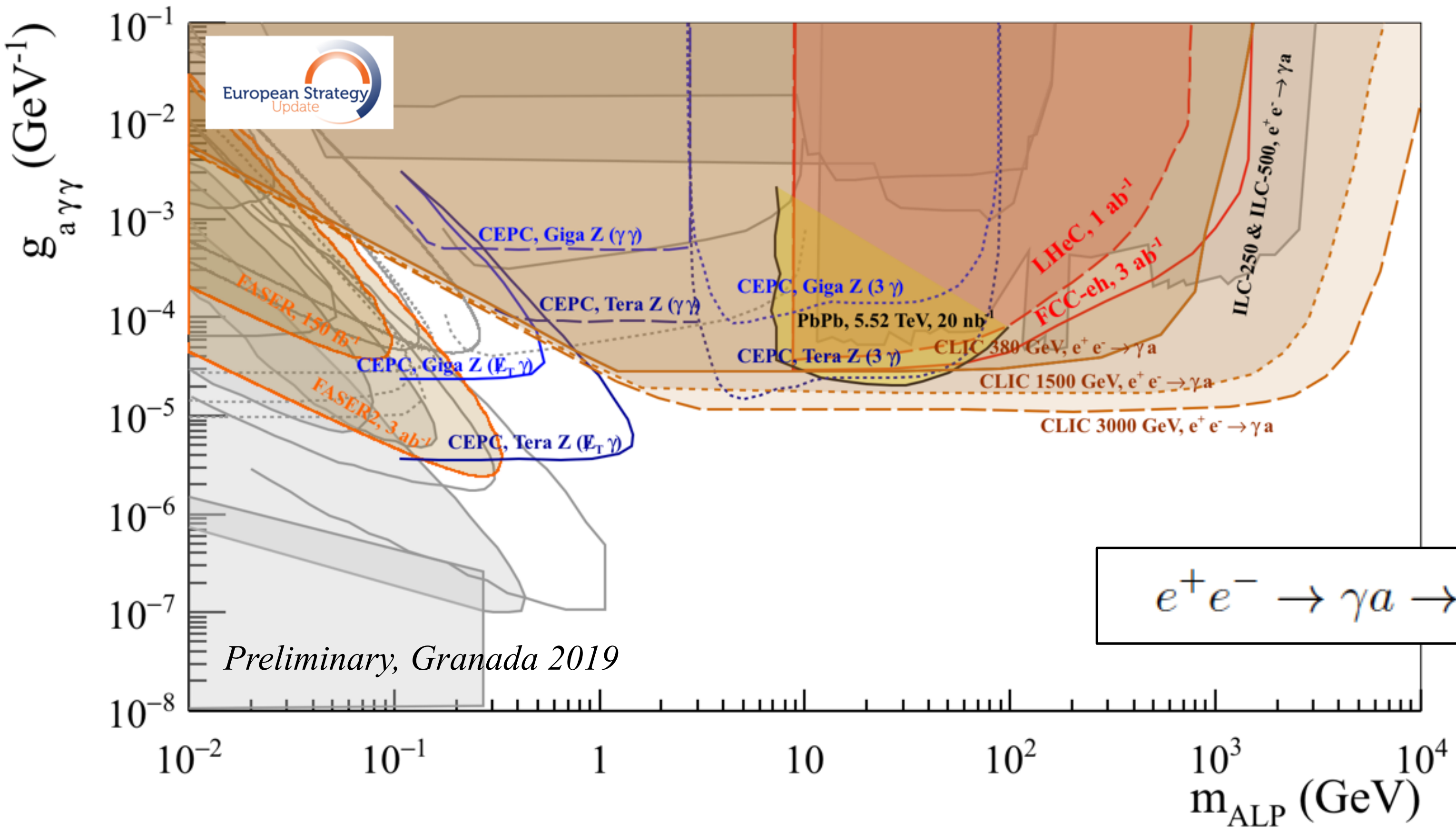


Source:
ILC Physics group
(Peskin et al.).

ILC-500 is comparable to CEPC with Tera-Z option in the high mass range.

Pseudo-Scalar portal: ALPs with photon coupling

Prospects for CLIC: 380 GeV (1 ab^{-1}), 1500 GeV (2.5 ab^{-1}), 3000 GeV (5 ab^{-1})



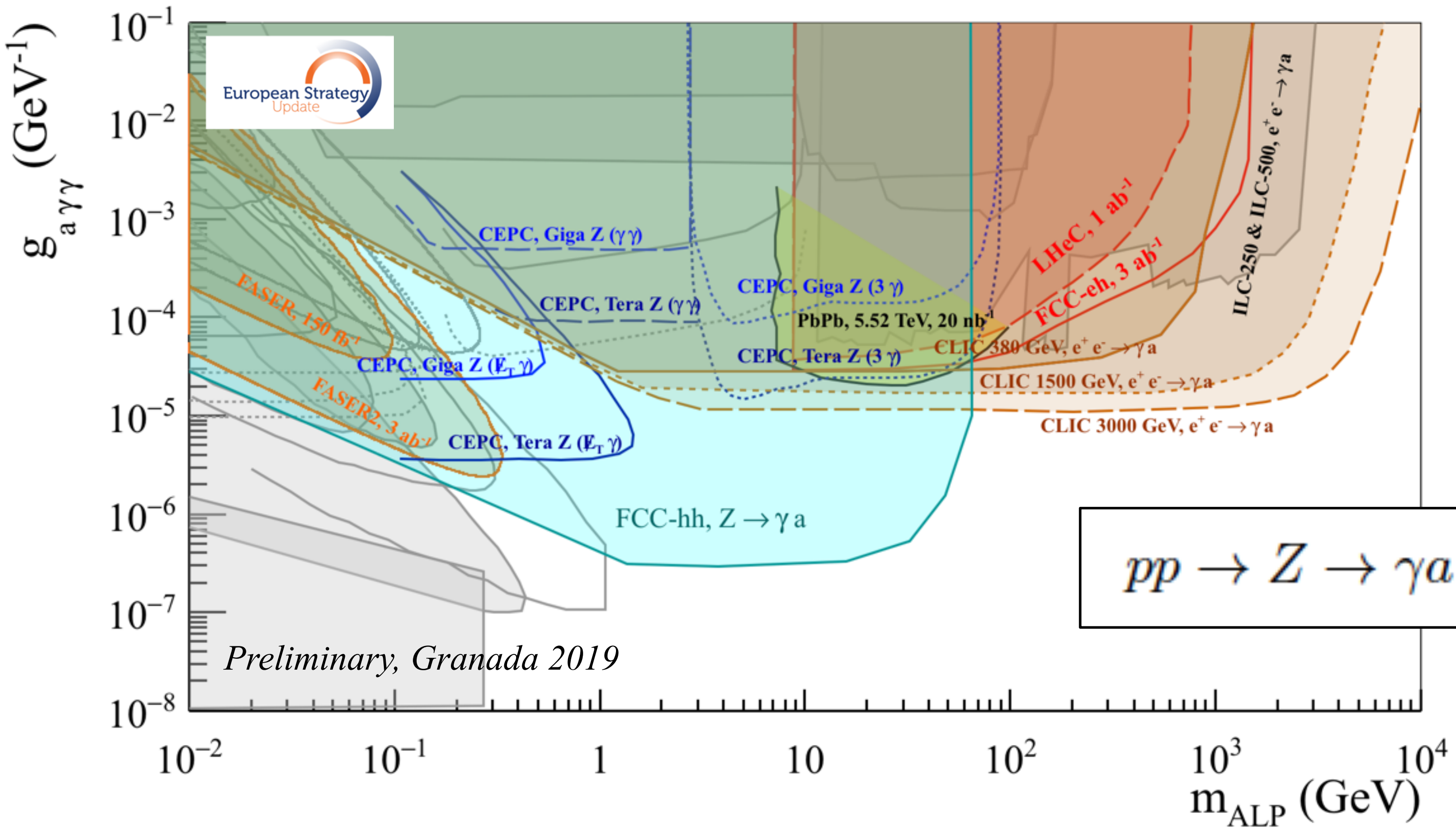
$$e^+e^- \to \gamma a \to 3\gamma$$

Source:
CLIC potential for New Physics, arXiv:1812.02093

CLIC (all stages) further push down the limits by almost an order of magnitude in the 10-1000 GeV range.

Pseudo-Scalar portal: ALPs with photon coupling

Prospects for FCC-hh (100 TeV, 20 ab^{-1})



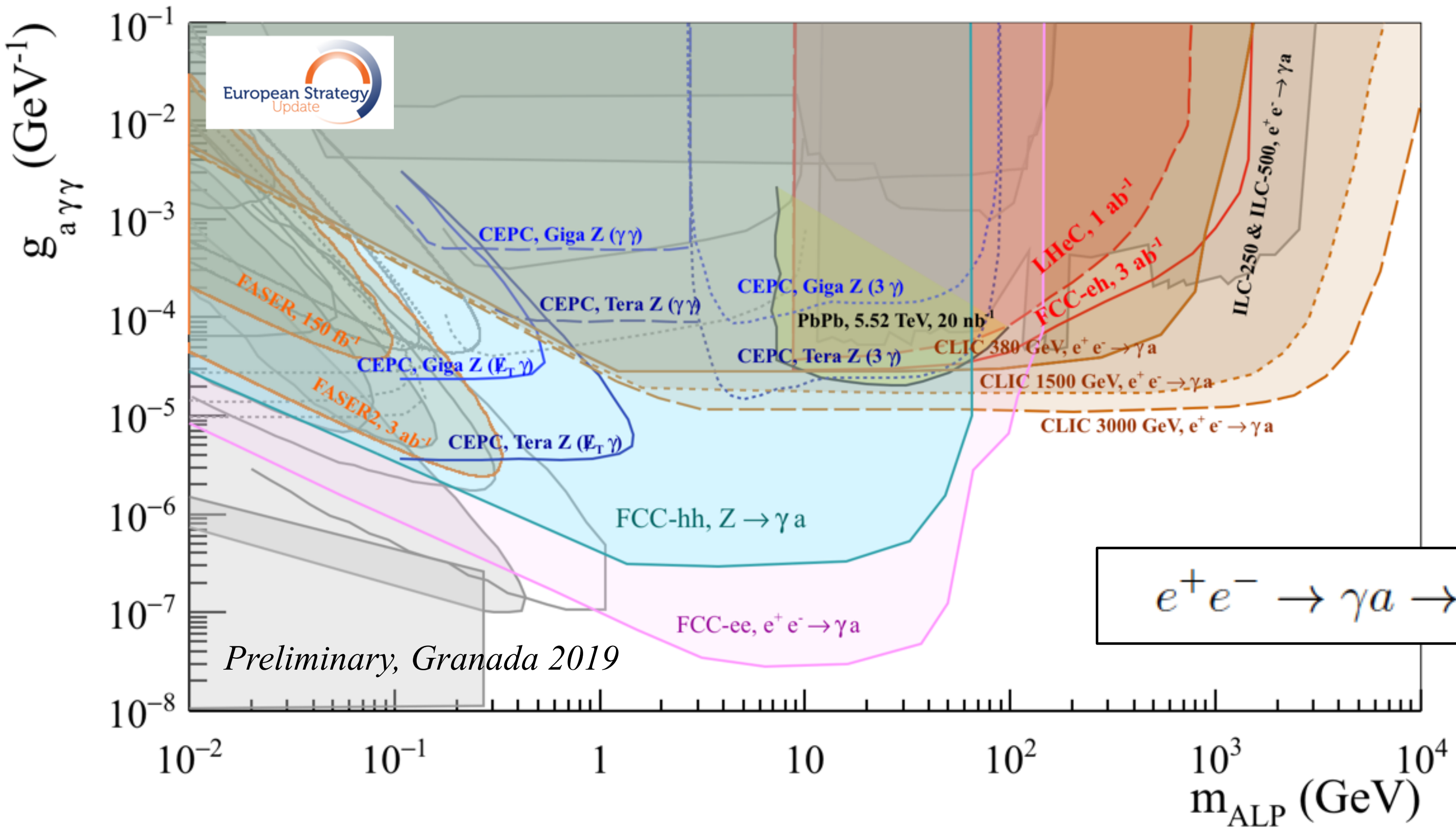
$$pp \to Z \to \gamma a \to 3\gamma$$

Source:
FCC Vol1,
CERN-ACC-2018-0056
(based on Bauer et al, arXiv:1808.10323)

FCC-hh can improve in the medium mass range (1-100) GeV.

Pseudo-Scalar portal: ALPs with photon coupling

Prospects for FCC-ee : combination of data at the Z-pole, 2 m_W and 240 GeV.



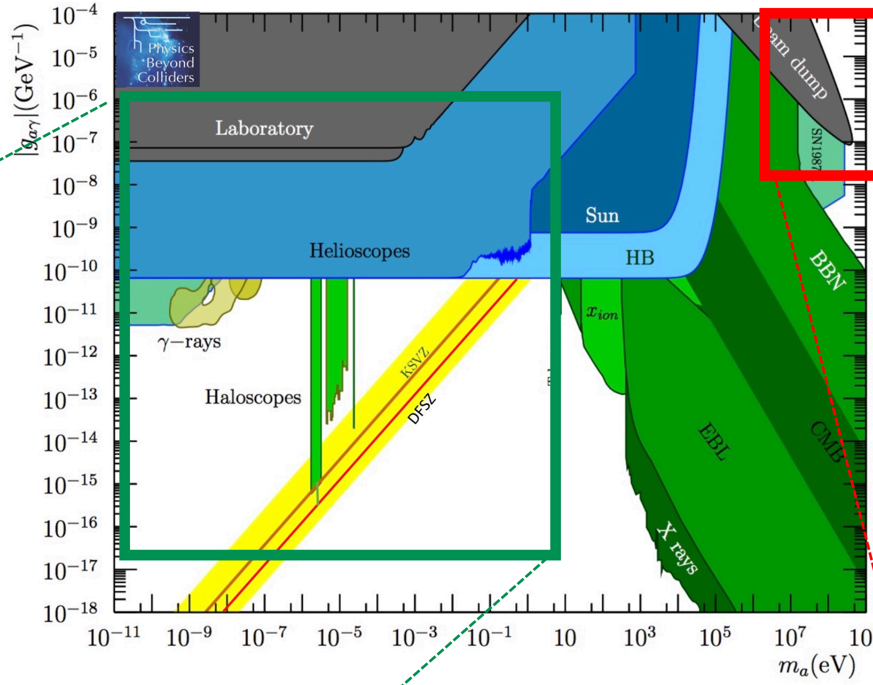
$$e^+e^- \to \gamma a \to 3\gamma$$

Source:
FCC-ee physics groups based on Bauer et al., arXiv:1808.10323

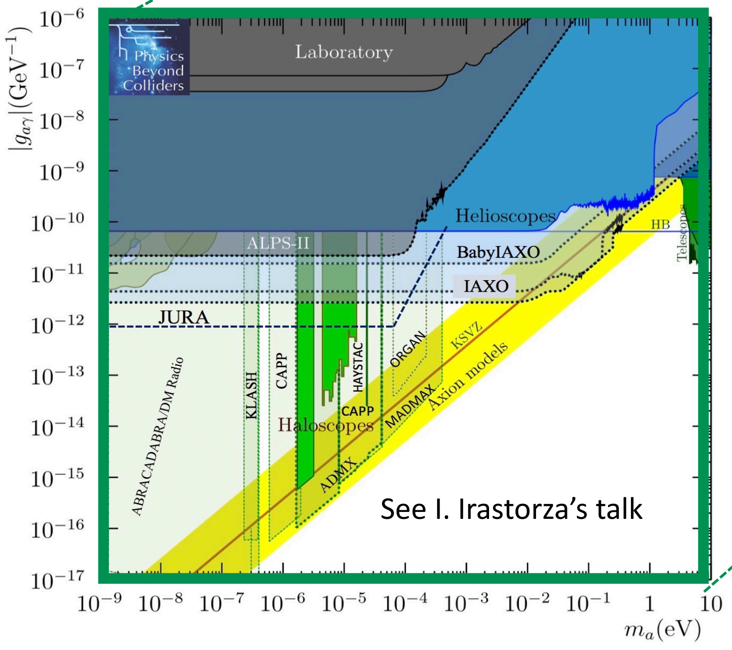
FCC-ee (all phases together) if the best option in the medium mass range.

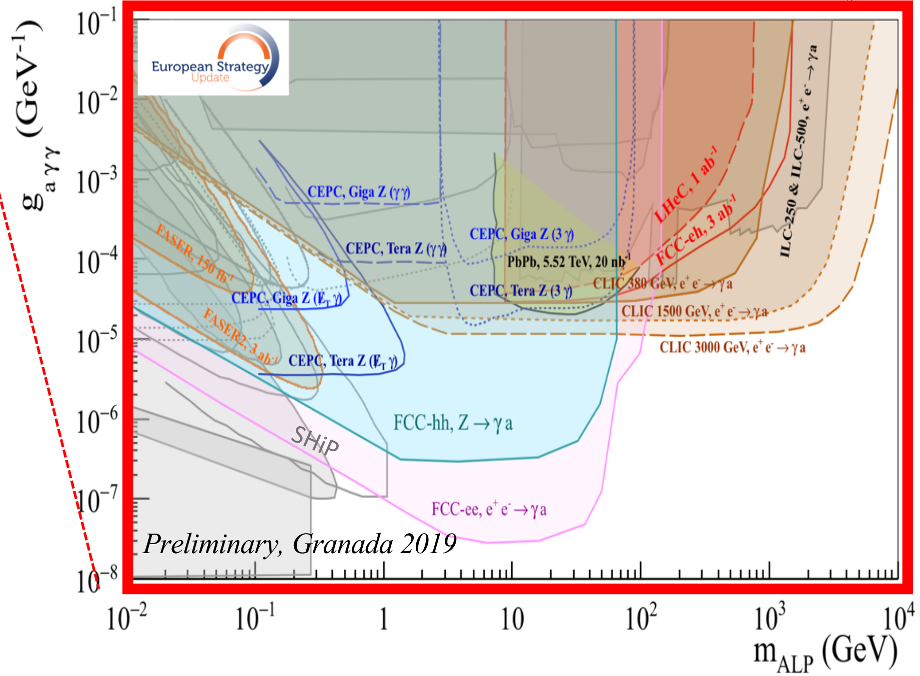
Pseudo-Scalar portal: ALPs with photon coupling

sub-eV range accessible at helioscopes and haloscopes



MeV-10 GeV range accessible at accelerators' based experiments





Nice complementarity of accelerator-based experiments, experiments in the sub-eV range, and cosmological bounds

Fermion portal
(sterile neutrinos)

$$y_N \, LHN$$

Asaka, Shaposhnikov, Drewes, Hernandez, Alekhin, Gorbunov, Lopez-Pavon, Bezrukov, Boyarsky, Ruchaysky, Rubakov, Smirnov, Atre, Han, Pascoli, Garbrecht, Kopp, Vissani. Strumia, Hambye, Akhmedov, Canetti, Frossard, Eijima, Chen, Mohapatra, Antusch, Bhupal-dev, Fischer + many others

Fermion Portal: possible physics motivation
Origin of the neutrino masses and oscillations

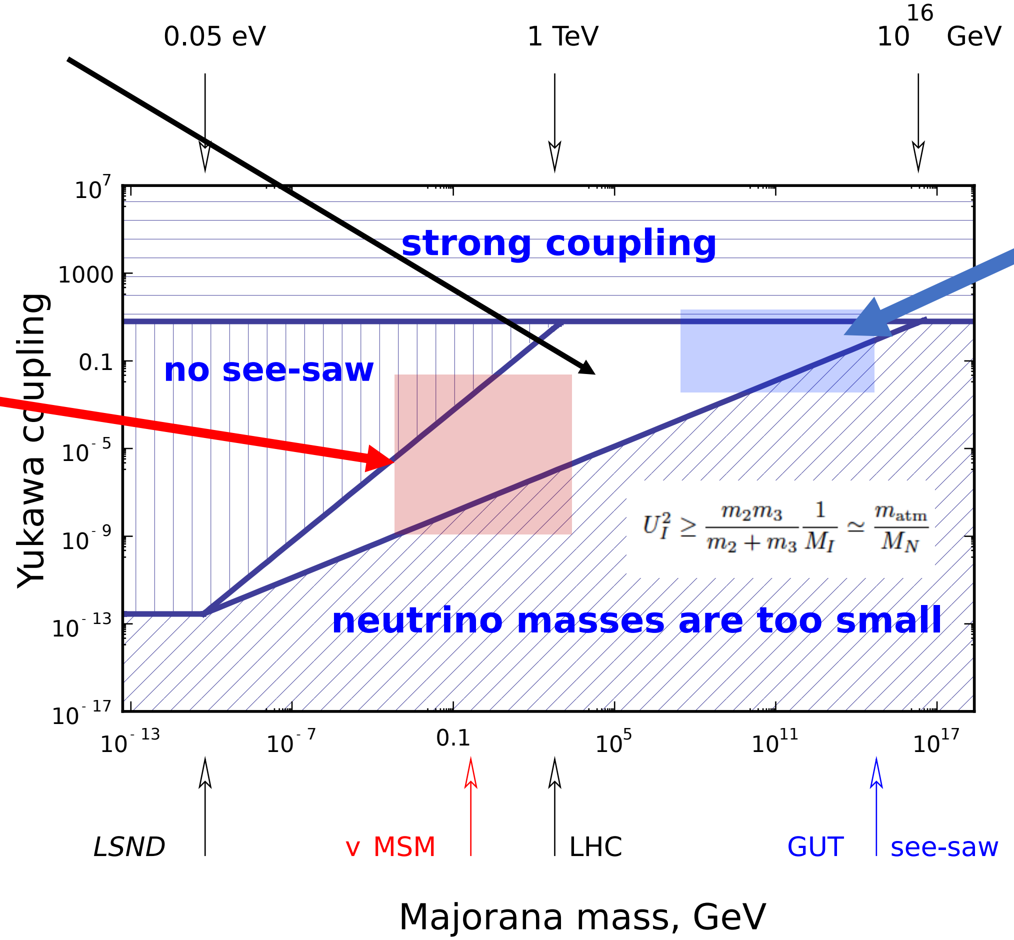
$SU(2)xU(1)_L$ singlet Right Handed Neutrinos responsible of the neutrinos' mass generation can have any coupling/mass in the white area, assuming an approximate $U(1)_L$ global symmetry

Shaposhnikov 0605047
Kersten,Smirnov: 0705.3221

Alternative choice:
EW "see-saw" (νMSM)

It is "natural" to assume that the masses of the RH neutrinos are below/around the EW scale

If 2 RHN have a mass degeneracy of o(10^{-2}) they could also explain baryogenesis via leptogenesis
Asaka, Shaposhnikov 0505013



Standard choice:
GUT see-saw

It "natural" to assume that Yukawa couplings of the RH neutrinos are similar to SM Yukawa.

$$M_N \simeq \frac{F^2 v^2}{m_{atm}} \simeq 6 \times 10^{14}\ \text{GeV}$$

Large spectrum of possible masses. We need a multi-scale approach.

Fermion Portal: Heavy Neutral Leptons below/around EW scale

Current limits and projections for beam dumps (eg: SHiP)

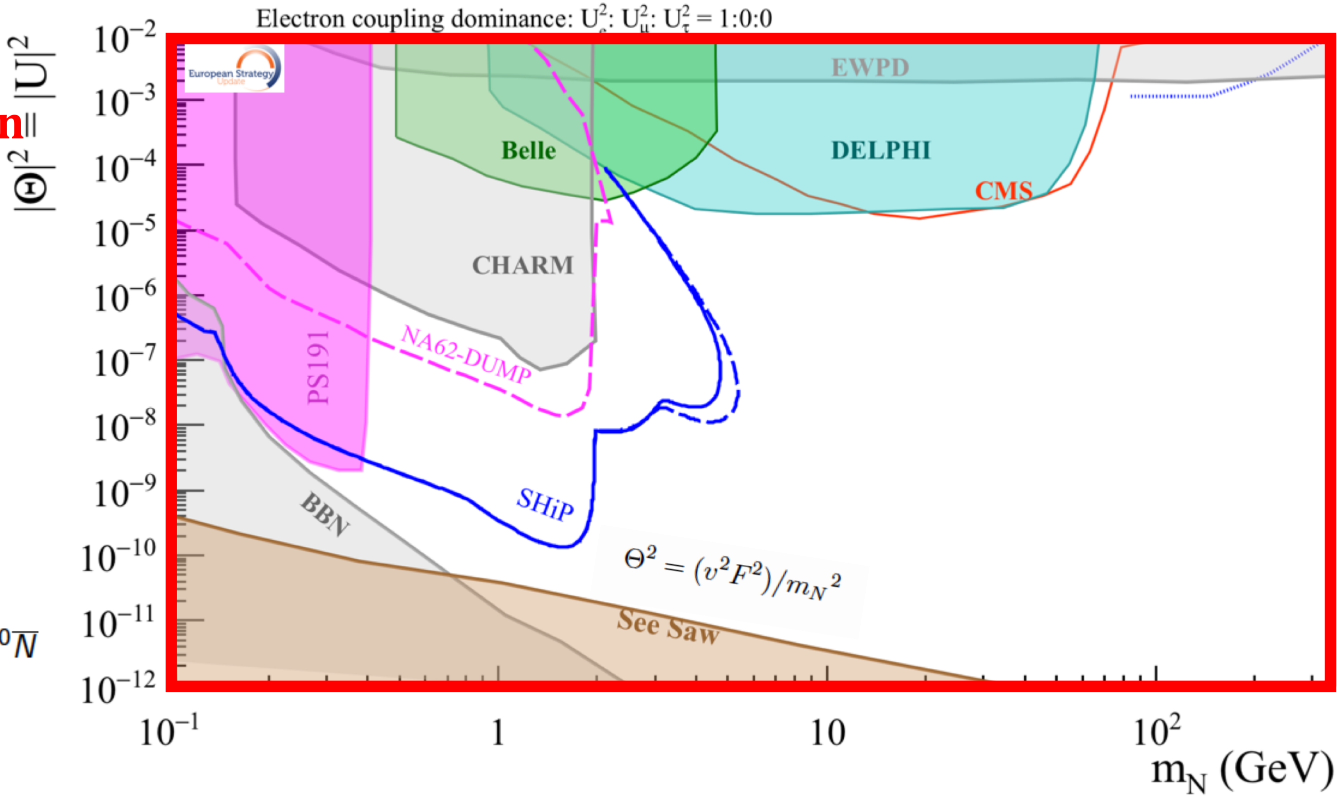
zoom in the MeV-100 GeV region

HNL-active neutrino mixing angles:

$$\Theta^2 = \theta_e^2 + \theta_\mu^2 + \theta_\tau^2$$

From:

$$\mathscr{L}_{\text{Yukawa}} = \sum_{\alpha=e,\mu,\tau} \theta_\alpha \frac{\sqrt{2}\,M}{v_{\text{EW}}} \nu_\alpha \phi^0 \overline{N}$$



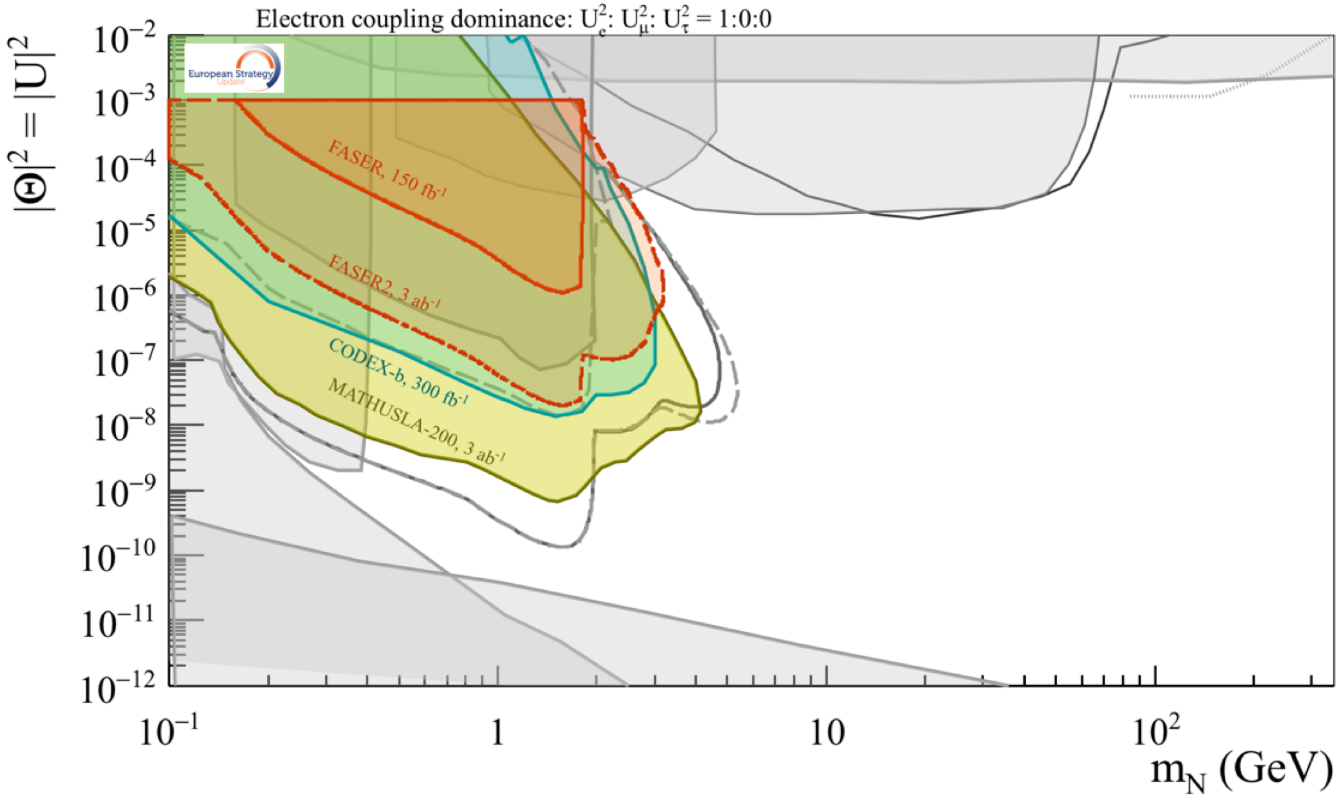
Source:
Physics Beyond Colliders BSM report, arXiv:1901.09966

Production occurs mostly via leptonic/semi-leptonic B,D decays. All visible decays modes considered.

SHiP can explore low-coupling, low-mass (< 5 GeV) range.

Fermion Portal: Heavy Neutral Leptons below/around EW scale

FASER (150 fb^{-1}, 3 ab^{-1}), CODEX-b (300 fb^{-1}) and MATHUSLA-200 (3 ab^{-1})



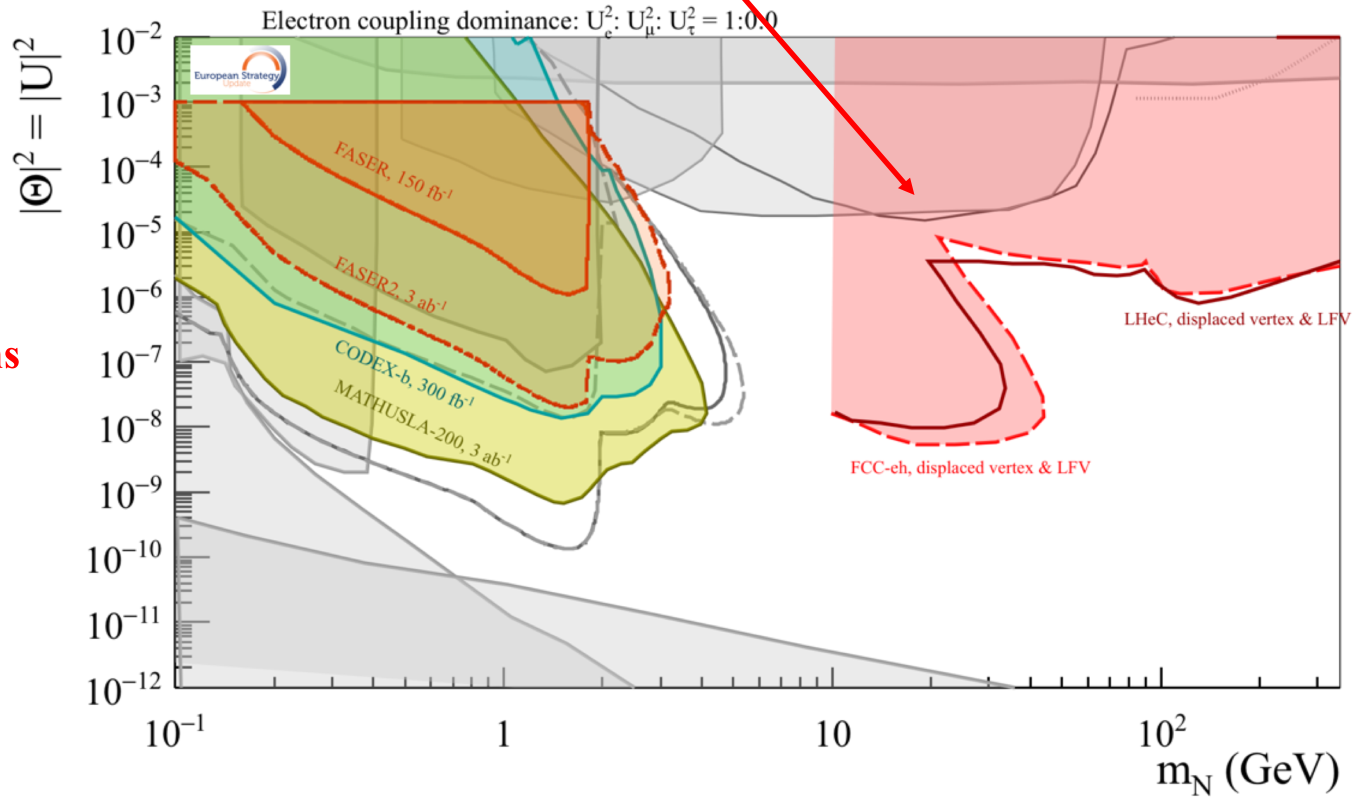
Source:
Physics Beyond Colliders BSM report, arXiv:1901.09966

Production occurs mostly via leptonic/semi-leptonic B,D decays. All visible decays modes considered.

FASER2, CODEX-b, MATHUSLA can also explore low-coupling, low-mass (< 5 GeV) range.

Fermion Portal: Heavy Neutral Leptons below/around EW scale

LHeC (1 ab^{-1}, 60 GeV e^-, 7 TeV p) and FCC-eh (3 ab^{-1}, 60 GeV e^-, 50 TeV p)



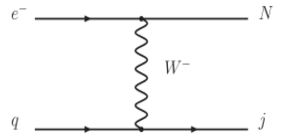
Sources:

1. Submission #159 to ESPP "Exploring the Energy Frontier with Deep Inelastic Scattering at the LHC,"
2. FCC report, Vol.2 CERN-ACC-2018-0057

Both based on arXiv:1612.02728

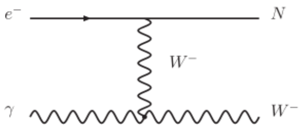
Production mechanisms at e p colliders:

T-channel W boson exchange



production channel: $\mathbf{W_t}^{(q)}$

γ W boson fusion

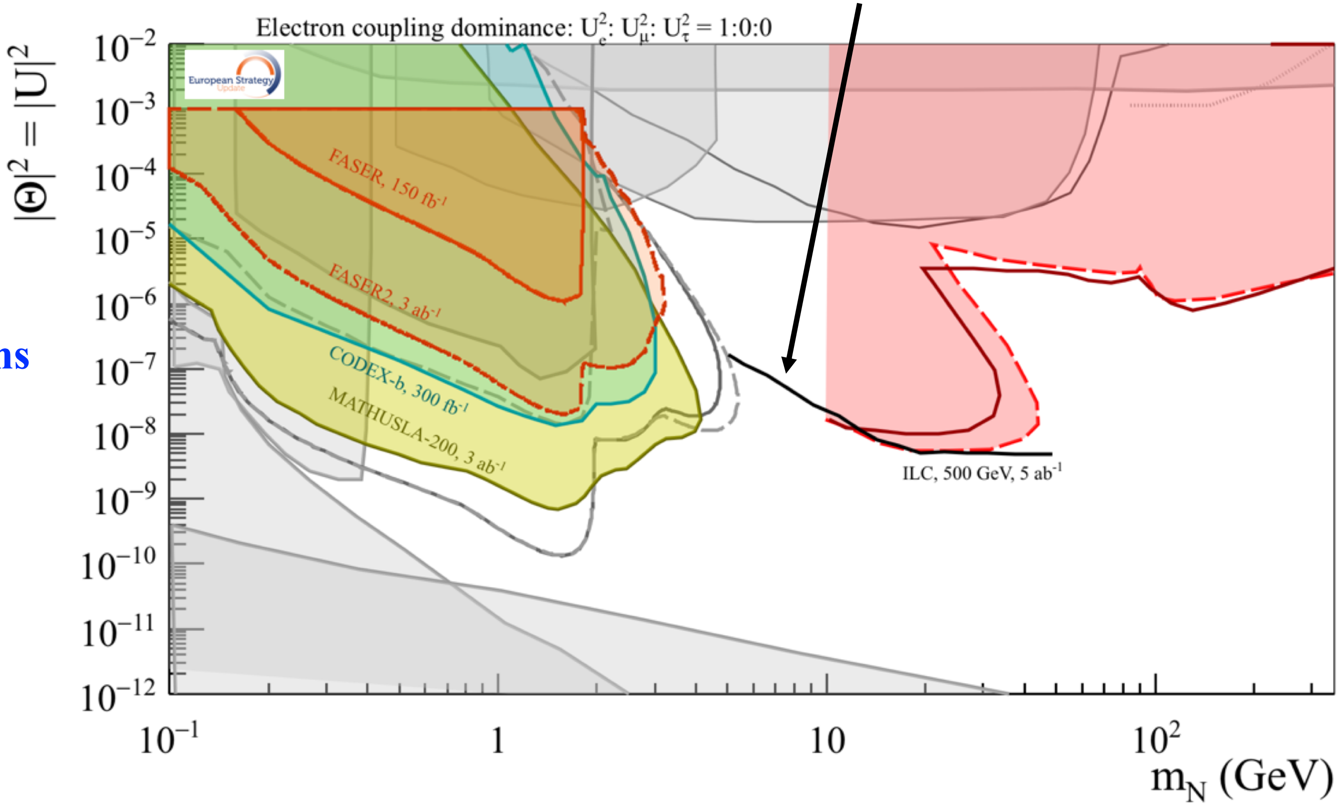


production channel: $\mathbf{W_t}^{(\gamma)}$

LHeC and FCC-eh can explore low-coupling, high-mass (> 10 GeV) range.

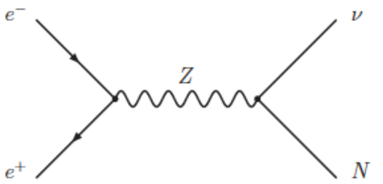
Fermion Portal: Heavy Neutral Leptons below/around EW scale

Prospects for ILC-500, 5 ab^{-1}

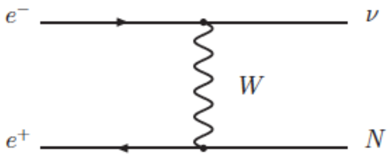


Source:
The ILC physics group (Peskin et al.)
Based on Antusch et al., 1710.03744

Production mechanisms at $e^+ e^-$ colliders:



production channel: $\mathbf{Z_s}$



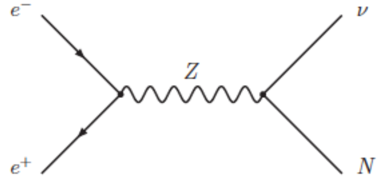
production channel: $\mathbf{W_t}$

ILC can fill the gap between low-mass (< 5 GeV) and high-mass (> 10 GeV) regions

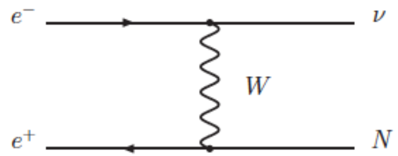
Fermion Portal: Heavy Neutral Leptons below/around EW scale

Prospects for CEPC: 10 ab^{-1} at the Z-pole and 5 ab^{-1} at 240 GeV.

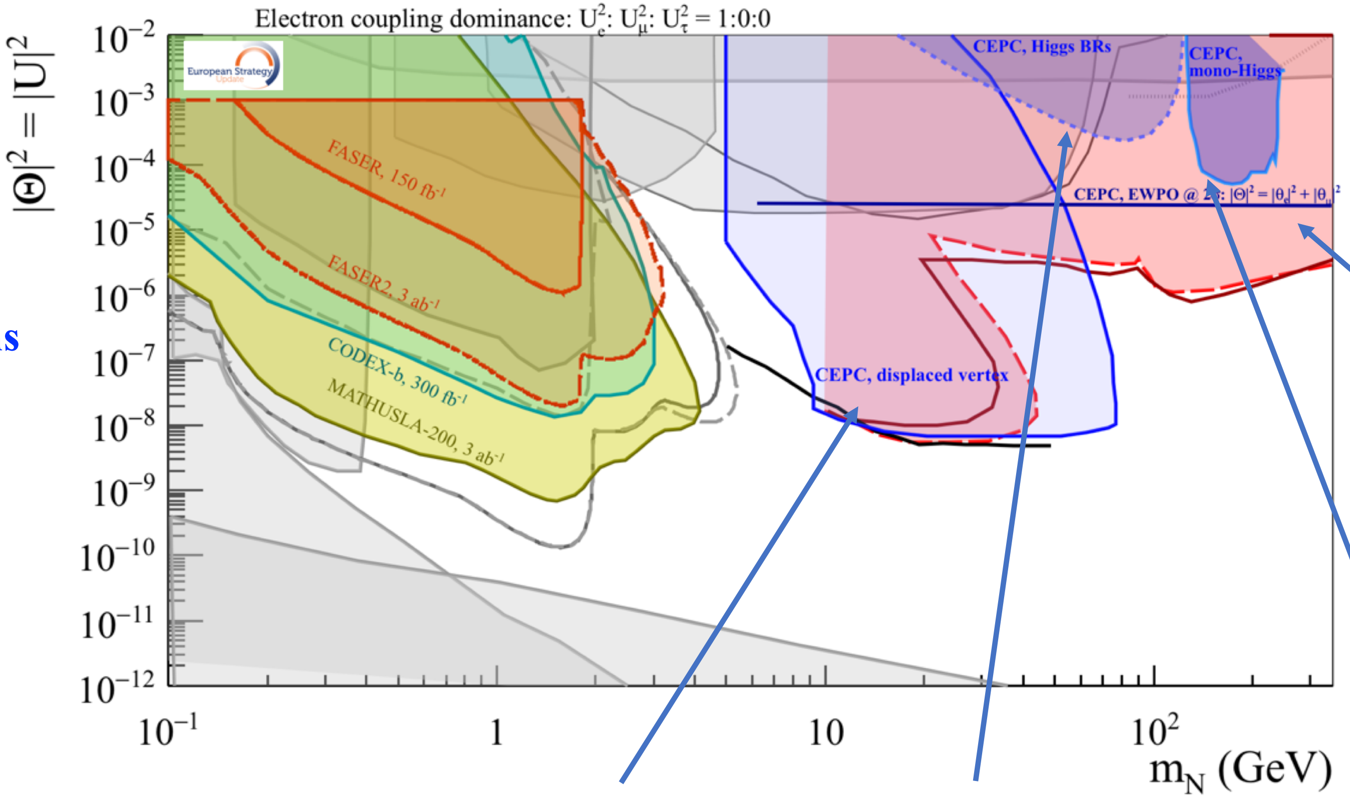
Production mechanisms at $e^+ e^-$ colliders:



production channel: Z_s



production channel: W_t



Displaced vertex searches:
Several decay modes accessible

Higgs BR:
presence of HNL modifies the Higgs width and BRs. The more sensitive is the $H \longrightarrow WW$ which constrains $H \longrightarrow \nu N$ (and Θ^2)

Source:
CEPC report, arXiv: 1811.10545
Based on arXiv:1612.02728

EWPO:
The PMNS matrix in presence of HNLs is not unitary. Modification of the theory prediction of precision observables. Present constraints include: EWPO, lepton universality, charged LFV, CKM unitarity

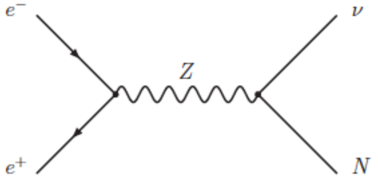
Mono-Higgs:
if m_N is above the Higgs mass,
$N \longrightarrow \nu \; H$, $H \longrightarrow$ hadronically (dijet).

European Strategy Update

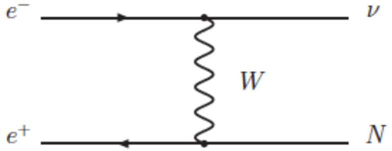
Fermion Portal: Heavy Neutral Leptons below/around EW scale

Prospects for FCC-ee : combination of data at the Z-pole (110 ab^{-1}), 2 m_W (7.5 ab^{-1}) and 240 GeV (5 ab^{-1}).

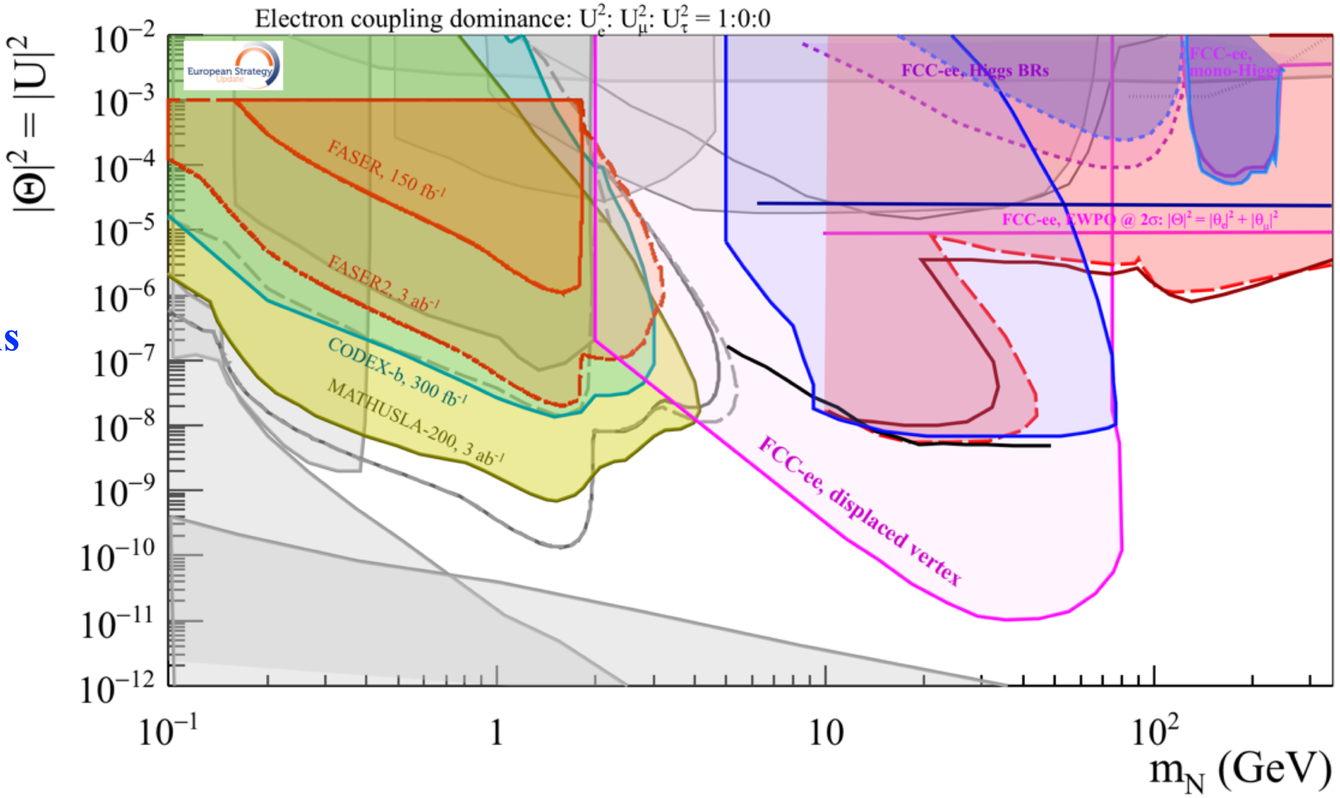
Production mechanisms at $e^+ e^-$ colliders:



production channel: Z_s



production channel: W_t

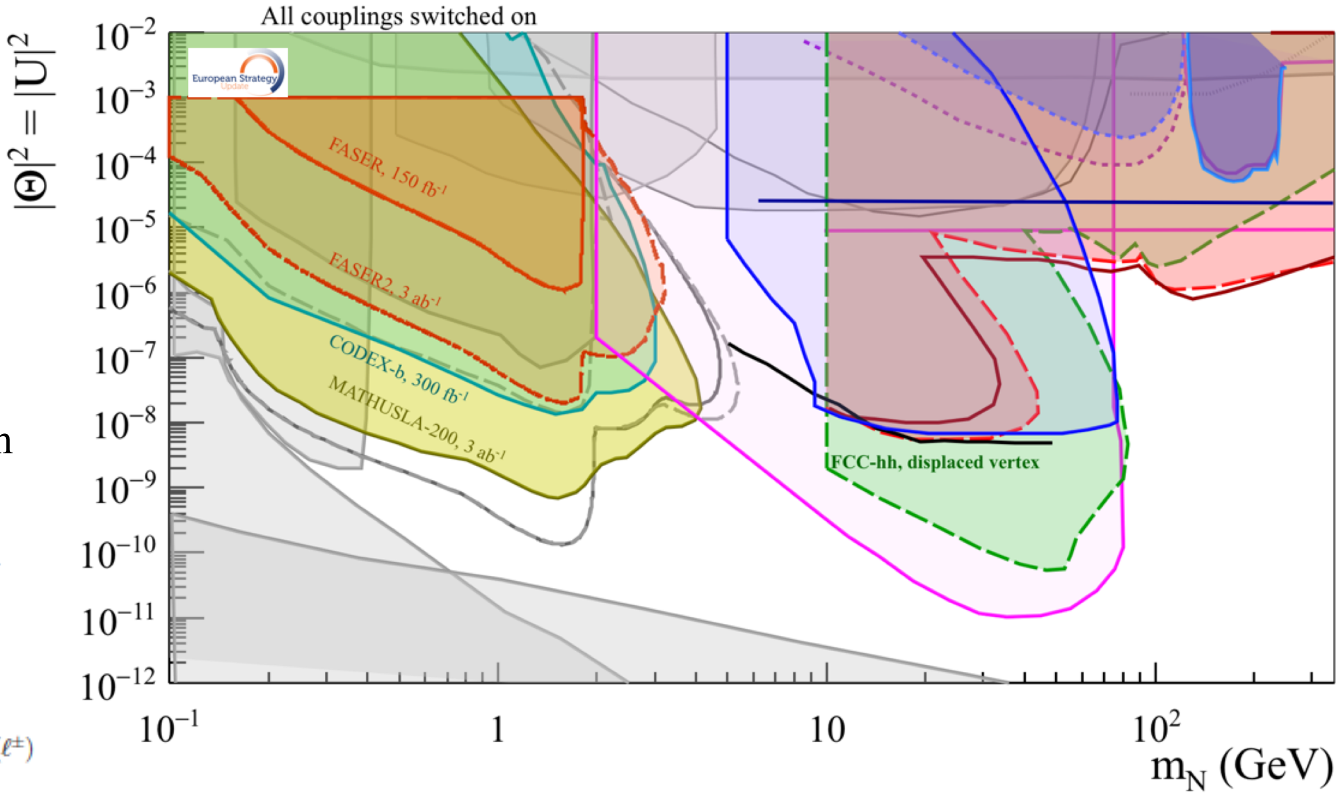


Source:
FCC report, CERN-ACC-2018-0057 (based on Antusch et al., arXiv:1612.02728)

FCC-ee is highly competitive when running at the Z-pole

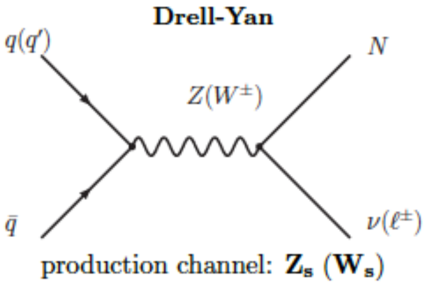
Fermion Portal: Heavy Neutral Leptons below/around EW scale

Prospects for FCC-hh: 100 TeV, 20 ab^{-1}



Source:
FCC report,
CERN-ACC-2018-0057
(based on Antusch et al., arXiv:1612.02728)

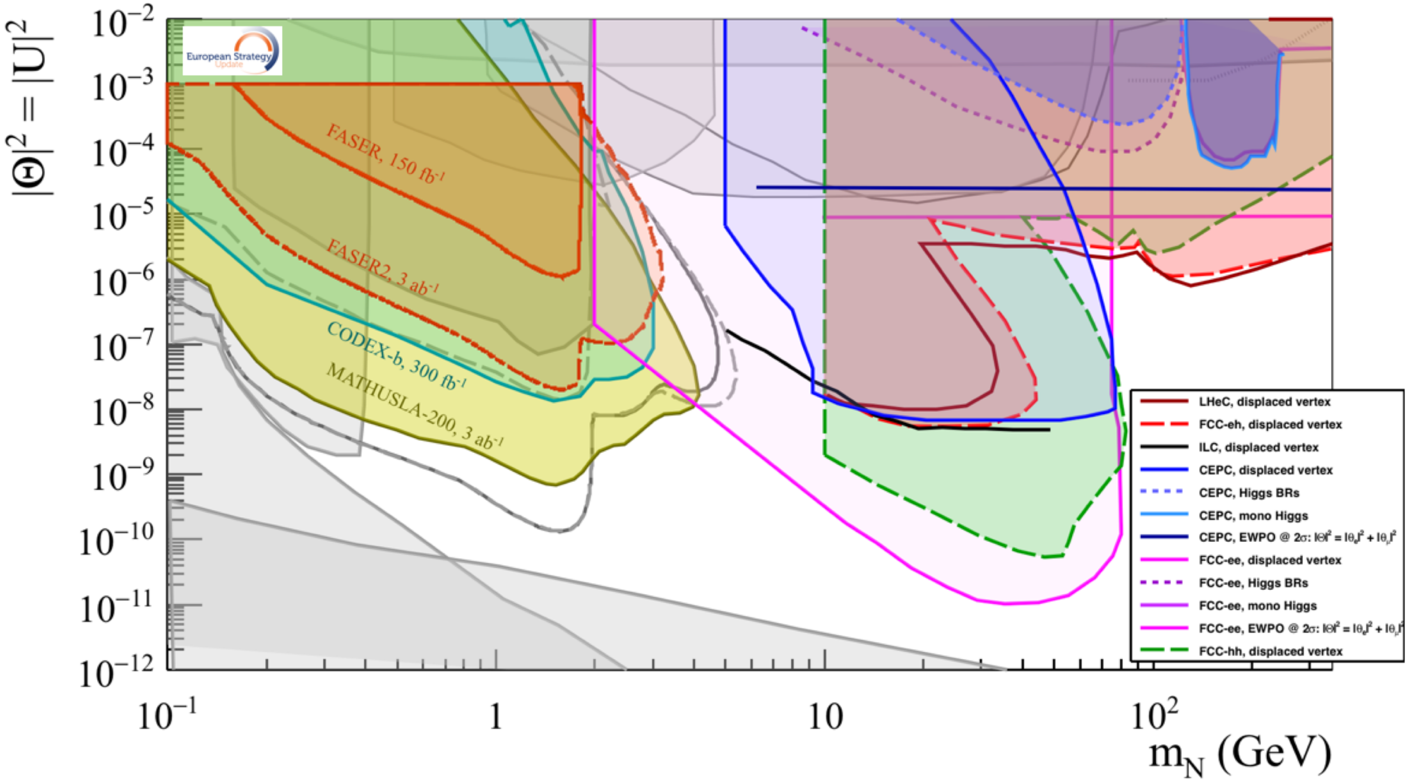
Production mechanism at p p colliders:



FCC-hh cannot improve with respect to e+ e- colliders below the Z threshold (but can improve at high masses, see later)

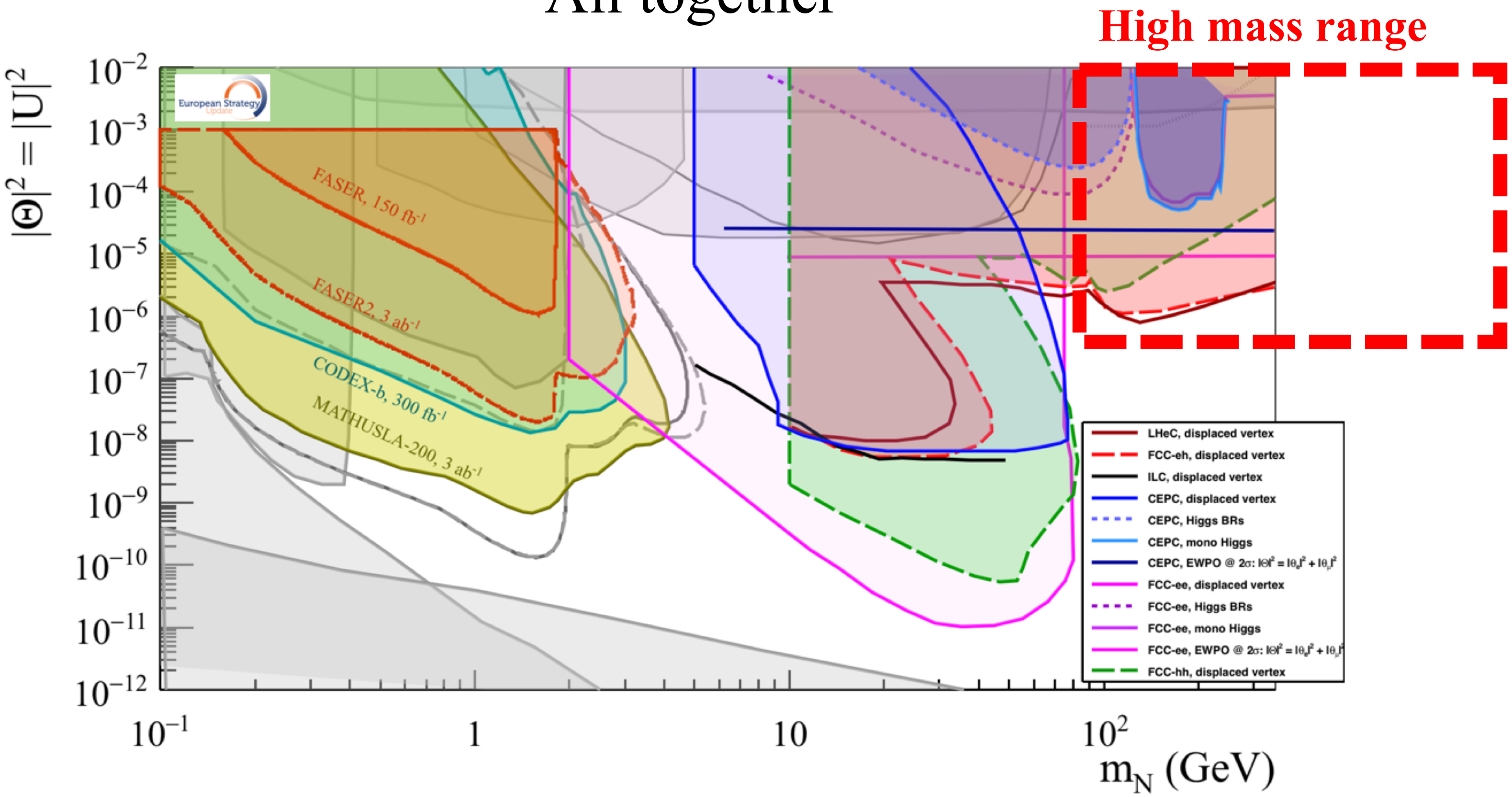
Fermion Portal: Heavy Neutral Leptons below/around EW scale

All together



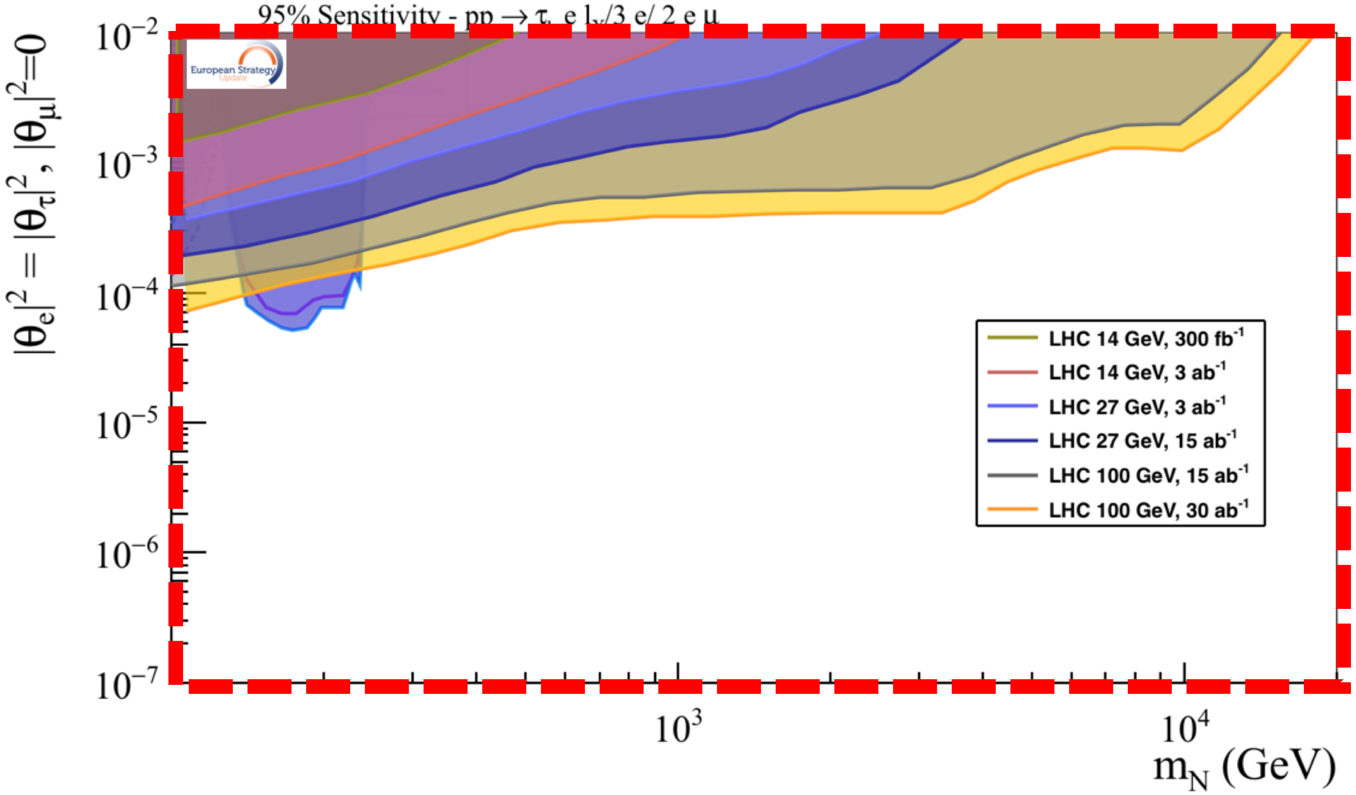
Nice complementarity between beam-dump and colliders' experiments

All together



Nice complementarity between beam-dump and colliders' experiments

High mass range: LHC, HL-HC, HE-LHC, FCC-hh

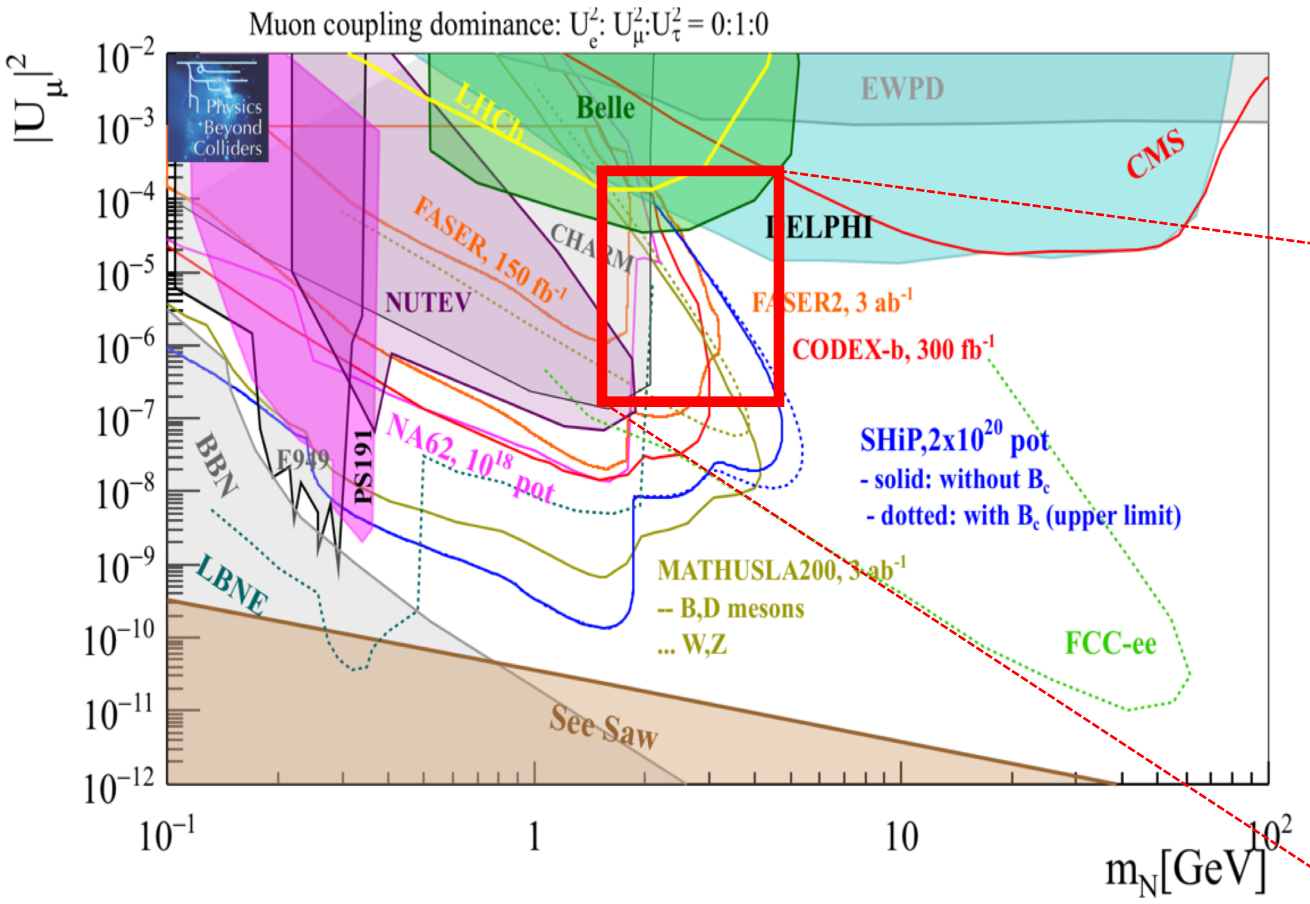


Source:
Beyond the Standard Model Physics at the HL-LHC and HE-LHC, arXiv:1812.07831

Hadron colliders can cover large-coupling in the high-mass range

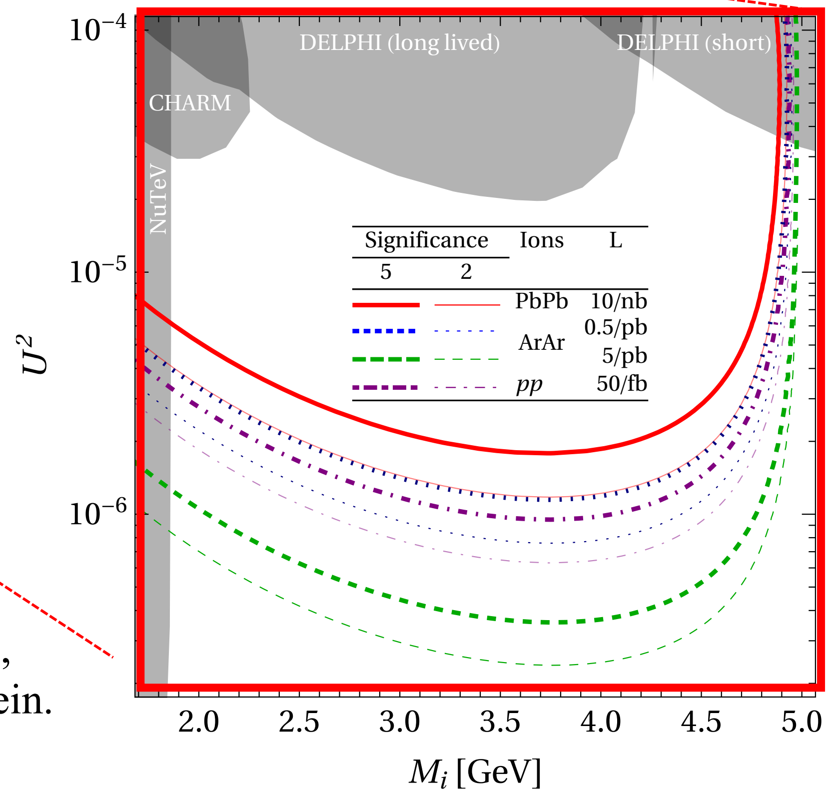
Fermion Portal: Heavy Neutral Leptons below/around EW scale

HNL with muon coupling



Heavy Ions prospects in Run 4 and beyond:

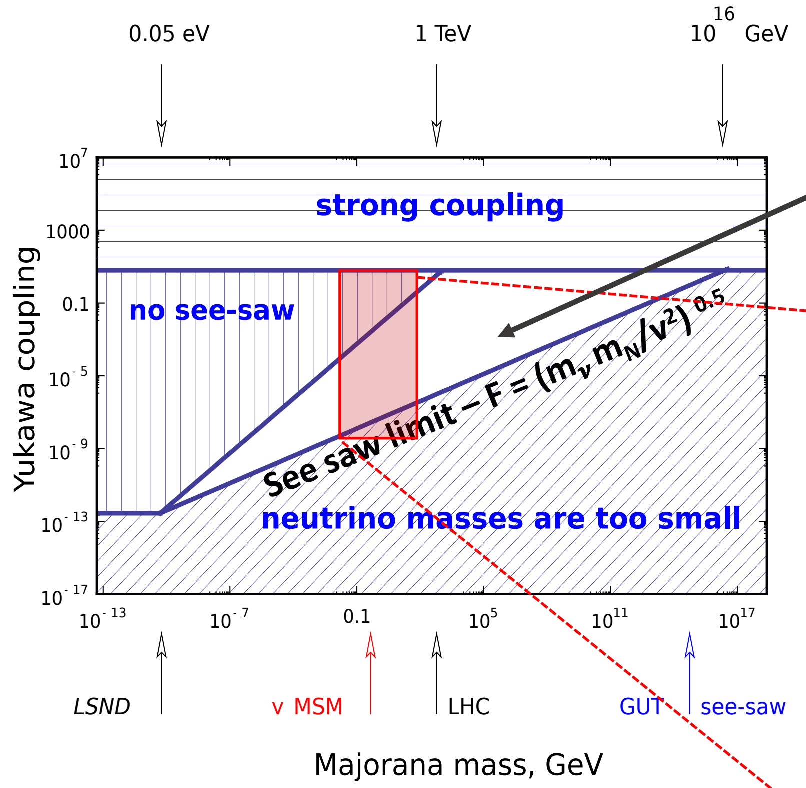
Best performance expected with 5/pb Ar Ar collisions.



Source:

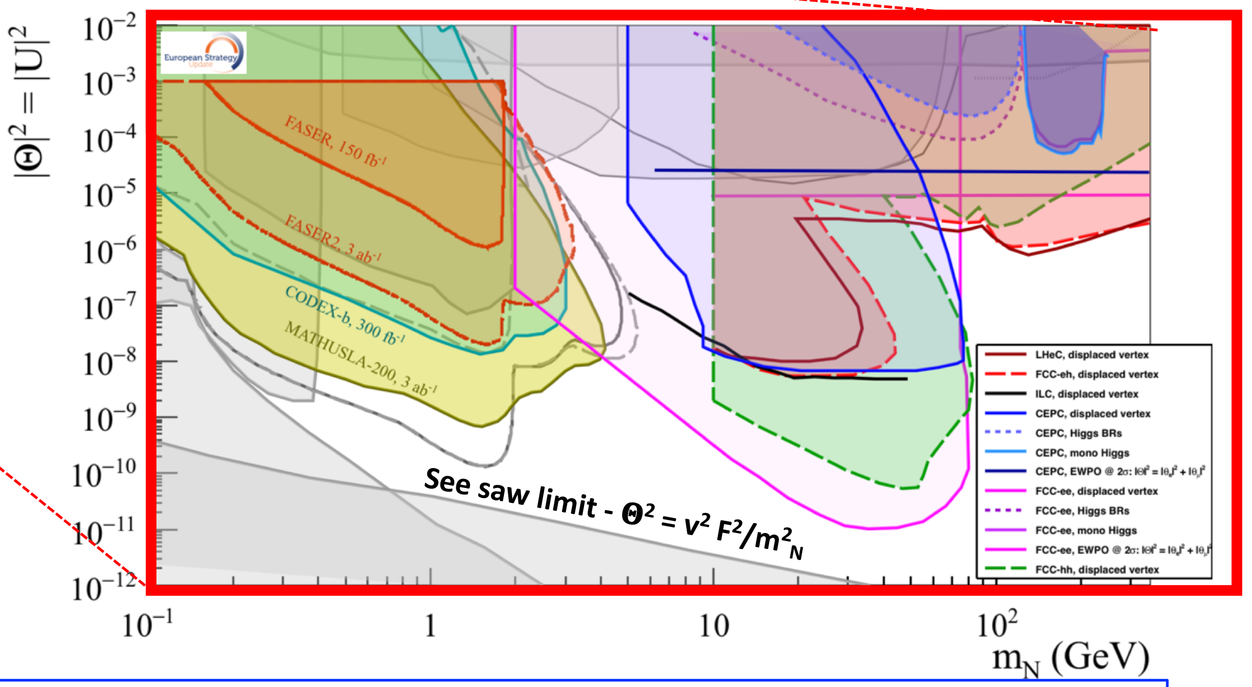
New Physics in Heavy Ions collisions, ESPP input # 151 and references therein.

Fermion Portal: possible physics motivation
Origin of the neutrino masses and oscillations



Back to the initial plot:

SU(2)xU(1)$_L$ singlet Right Handed Neutrinos responsible of the neutrinos' mass generation can have any coupling/mass in the white area, assuming an approximate U(1)$_L$ global symmetry.



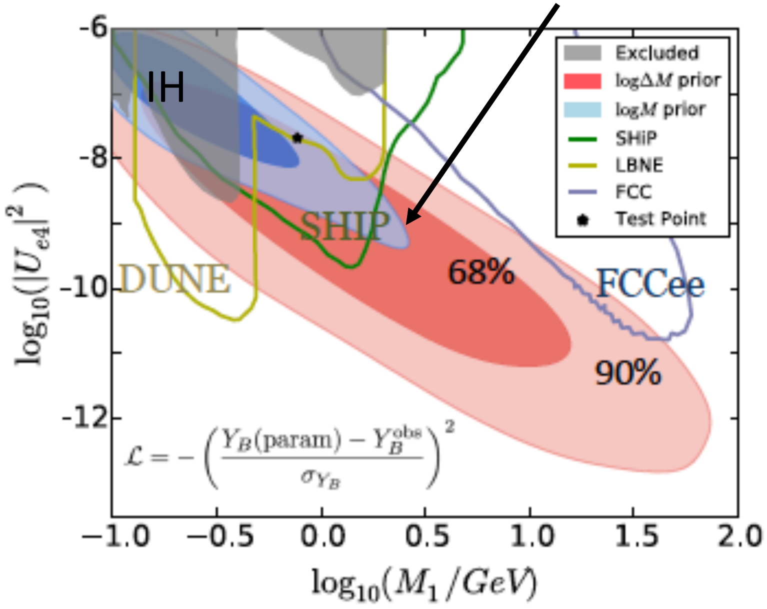
With beam dump and future colliders's experiments we can explore (light) RHN in the mass range 0.1-90 GeV almost down to the see-saw limit.

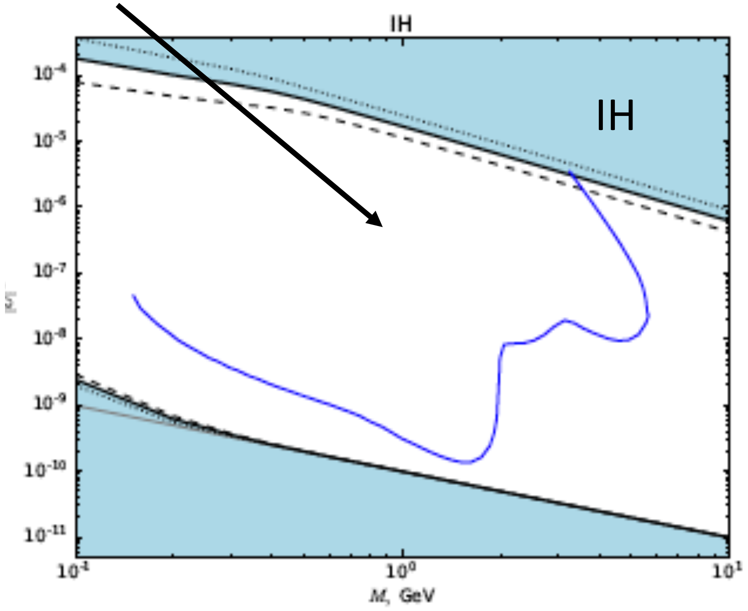
Fermion Portal: a possible connection to leptogenesis

- ✓ **Initial idea:** Akhmedov, Rubakov, Smirnov 98
- ✓ **Formulation of kinetic theory and demonstration that NuMSM can explain neutrino masses, Dark matter and baryon asymmetry:** Asaka Shaposhnikov 05
- ✓ **Analysis of baryon asymmetry generation in the NuMSM:** Asaka, Shaposhnikov, Canetti, Frossard, Abada, Domcke, Lucente, Hernandez, Racker, Salvado, Drewes, Garbrech, Guetera, Klaric, Hambye, Eijima, Timiryasov, …

Regions compatible with leptogenesis

P. Hernandez et al, arXiv:1606.06719





Eijima, Shaposhnikov, Timiryasov, 1808.10833

Region compatible with leptogenesis is accessible at accelerator based experiments.

Conclusions

Conclusions

- ✓ Feebly interacting particles are generically motivated in a broad class of models:
  ⟶ they nicely complement the quest for New Physics in the high energy and flavor frontiers.

- ✓ No scale associated within this paradigm:
  ⟶ preferred mass/coupling regions are model-dependent.

- ✓ Four (vector, scalar, pseudo-scalar, fermion) portals provide a few, simple, gauge-invariant, (as much as possible) model-independent benchmarks cases to compare sensitivity across experiments over many orders of magnitudes:
  ⟶ a starting point.

- ✓ In the accelerator domain, collider based experiments nicely complement the physics reach at beam-dump experiments. But the field is much broader:
  ⟶ connection with neutrino-physics, cLFV, axion searches at helioscopes/haloscopes, DM direct detection searches, table-top experiments, astrophysical observations, etc., etc.

The "feeble paradigm" is an important physics case for the future: to explore it we need a multi-scale (multi-experiment) approach

STOP

Questions to guide the discussion session

Questions to guide the discussion session - FIPs

1. To what extent can we test FIPs at accelerators ?
   i) log-crisis: we need a multi-scale & multi-experiment approach: call for a diversity program.
   ii) a concrete example: the four portals.
   iii) within the four portals we can investigate parameters regions that could address some fundamental theoretical and experimental problems eg: thermal DM, maximal mixing in relaxion models, RHN below the EW scale, etc.

2. Interplay:
   2a. what is the interplay between colliders and fixed-target/beam dump experiments
   2b. what is the interplay (beyond mere complementarity) between accelerators and low energy probes (neutrino physics , CPV-EDM, helioscopes, table top experiments etc ...).

3. Inverse problem:
   - if we get a FIP-like signal, how can we probe its nature?

Inputs from DM discussion session

The DD/astrophysics community would like to work in synergy with the future collider program of DM searches

How can CERN respond to the
DD community submission wishlist, as e.g. a:

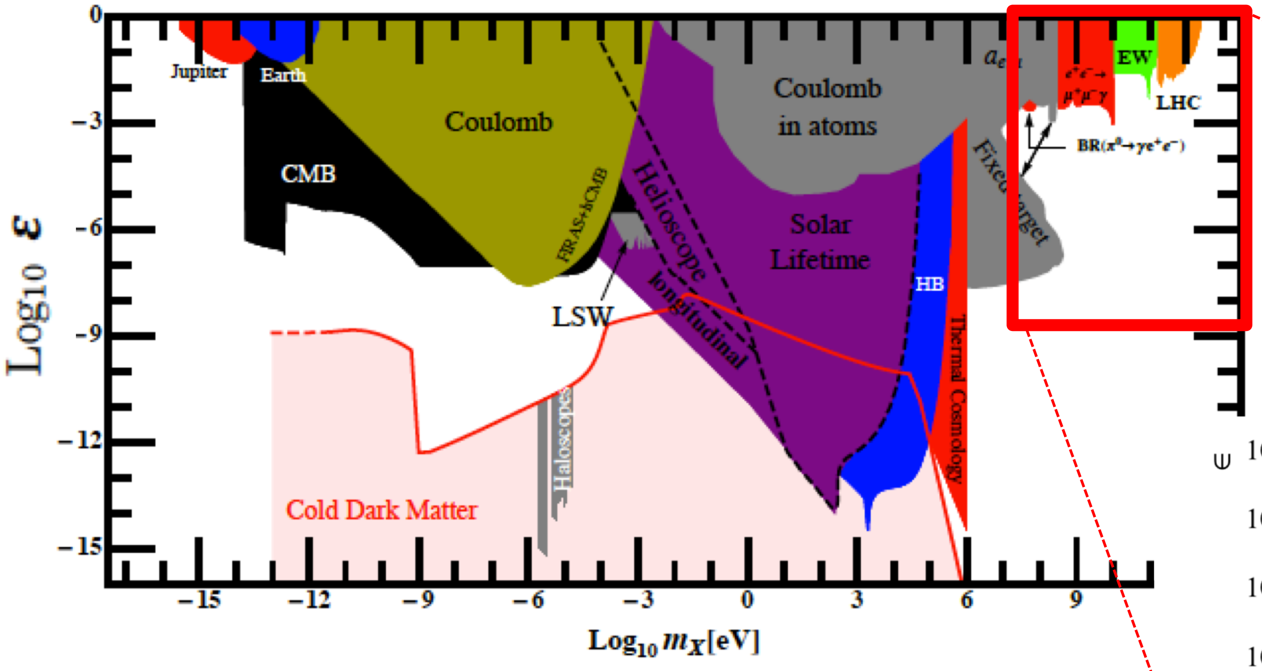
technology / science / theory hub
[J. Monroe's talk, computing session]
place to exchange software expertise
[C. Tunnell, HEP Software Foundation/OSG/WLCG workshop]
[also discussed in computing session]

Inputs from DM discussion session

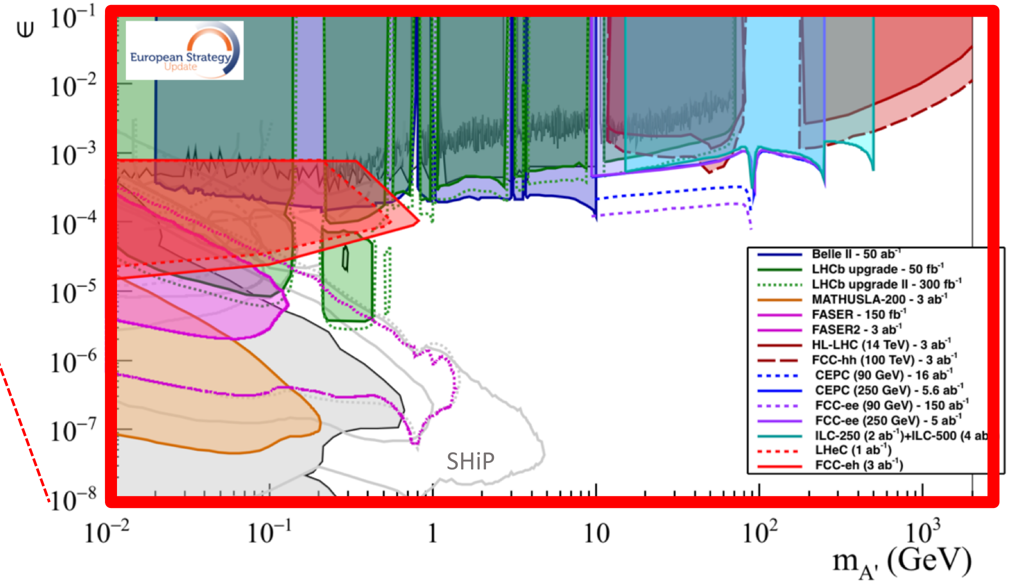
When is a FIMP model considered "Dark Matter"?

Should we use the relic density as a target or there are other astrophysical properties we could consider?

Vector portal: coverage and complementarity



MeV-TeV range accelerators' domain (range compatible with the hypothesis of DM as thermal relic)



Improvements by several orders of magnitude both in low-mass low-coupling regime (beam-dump) and in high-mass large-coupling regime (colliders).

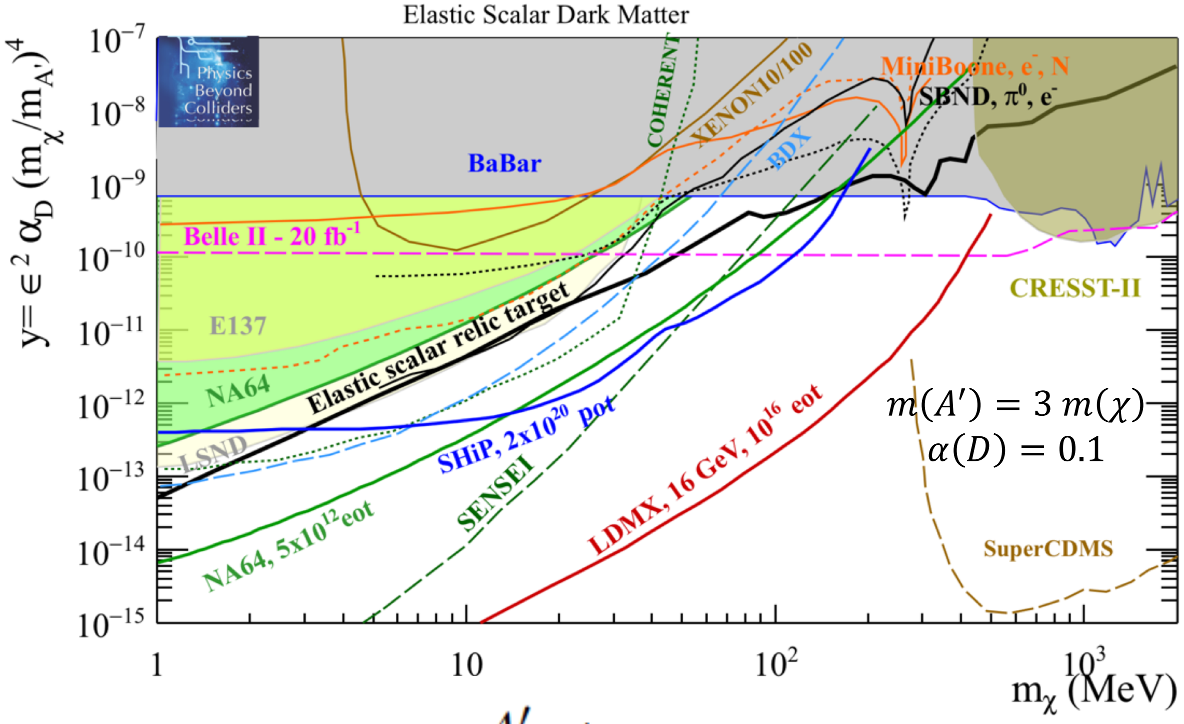
Nice complementarity between beam-dump and colliders' experiments

Vector Portal: interplay with Light Dark Matter DD experiments

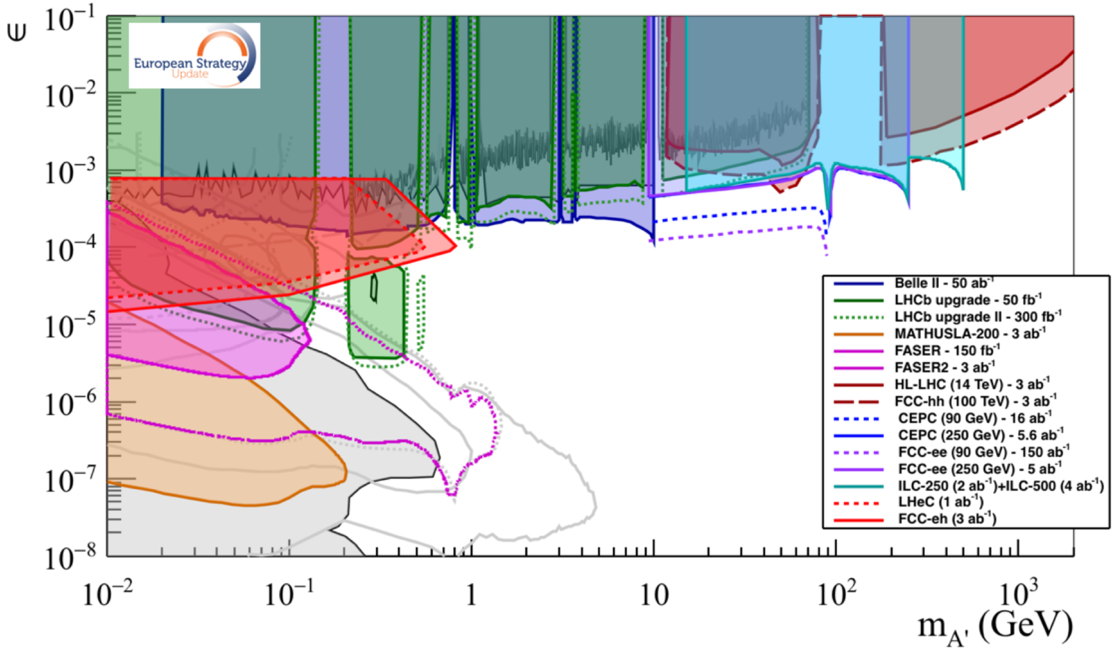
Model where minimally coupled viable WIMP dark matter model can be constructed.
The parameter space for this model is: $\{m_{A'}, \epsilon, m_\chi, \alpha_D\}$

$$\sigma v \sim \alpha_D \epsilon^2 \alpha \frac{m_\chi^4}{m_{A'}^4} \times \frac{1}{m_\chi^2}$$

PBC-BSM report, arXiv:1901.09966



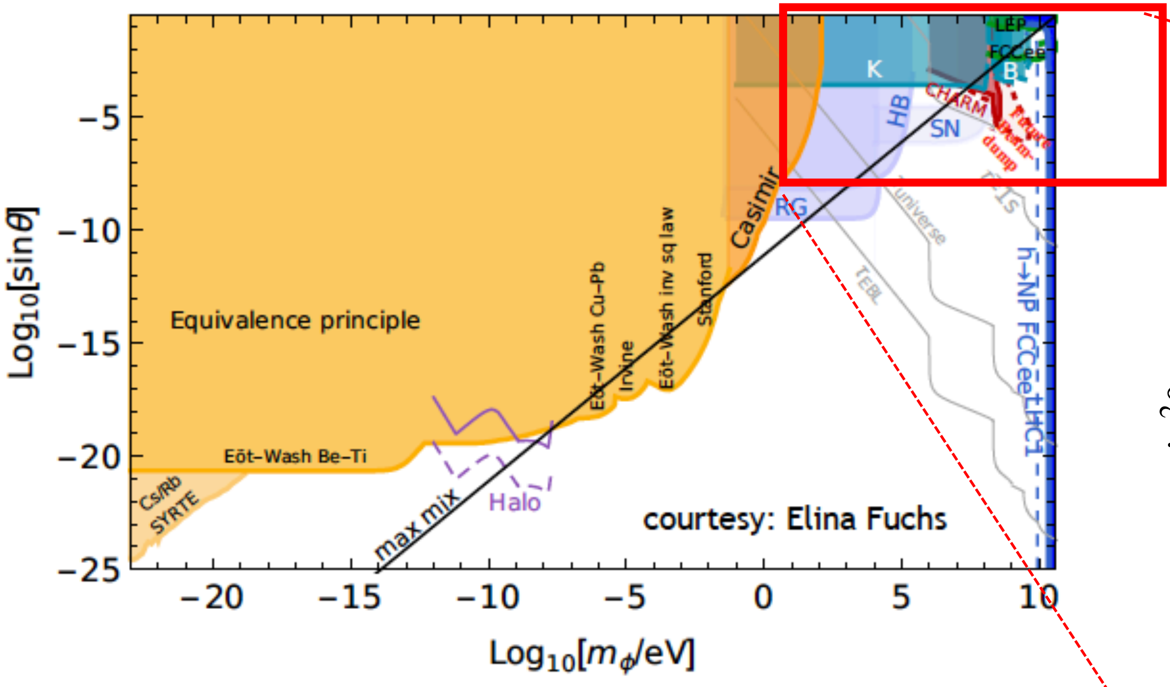
$A' \to \chi\chi$



$A' \to e^+e^-, \mu^+\mu^-$

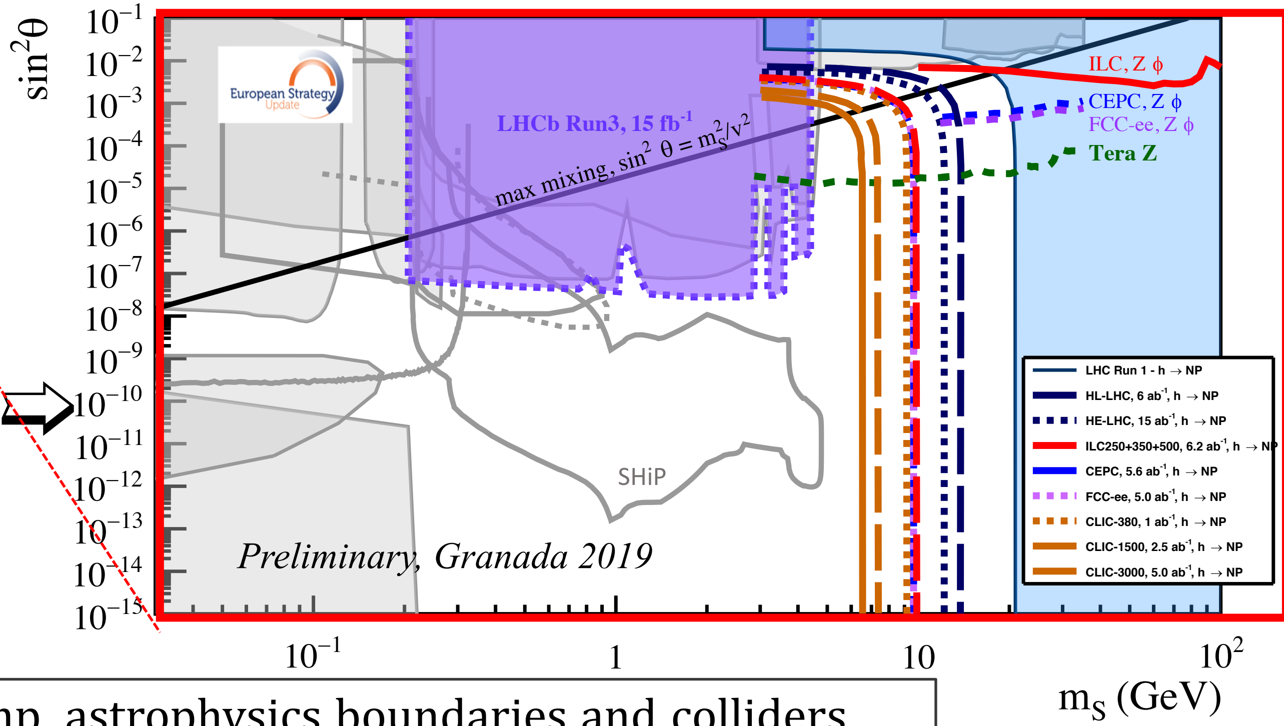
Nice complementarity between accelerator-based proposals, colliders and Light DM direct detection experiments.

Scalar Portal: coverage, complementarity, interplay



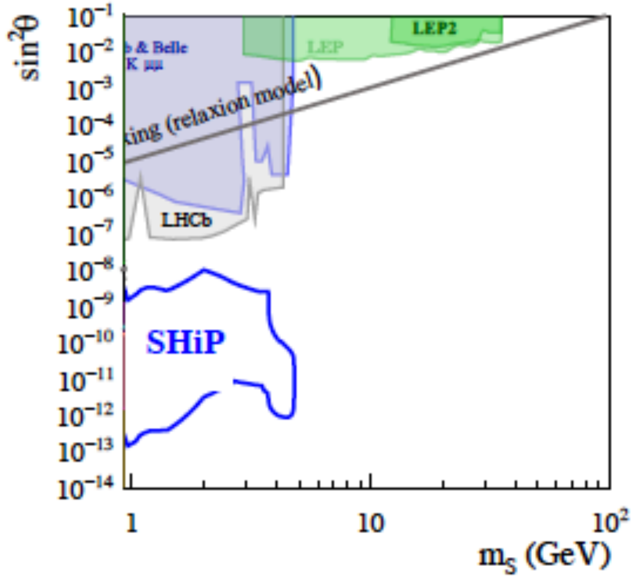
MeV-100 GeV range is accessible at accelerators' based experiments

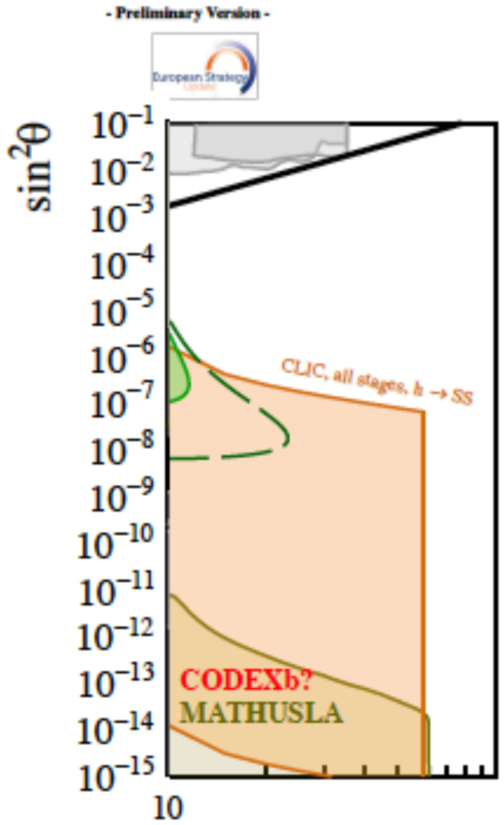
High-mass range can be excluded by the knowledge of the Higgs couplings; Improvements by several orders of magnitude possible in low-mass low-coupling regime using direct searches.

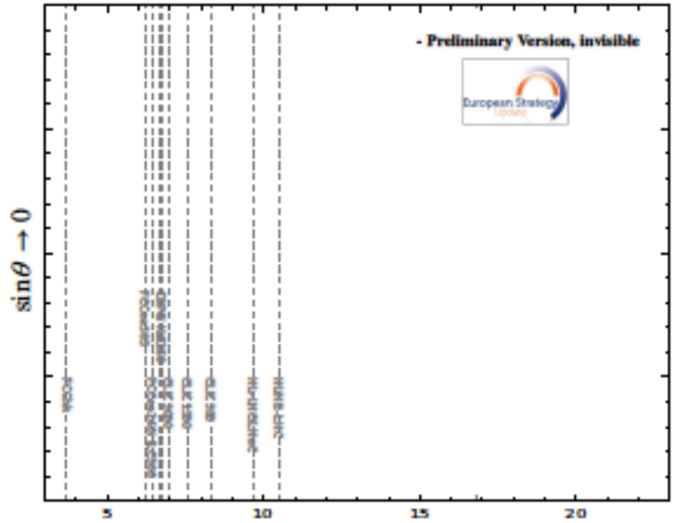


Nice complementarity between beam-dump, astrophysics boundaries and colliders. Together they can explore a large fraction of the "natural" relaxion region.

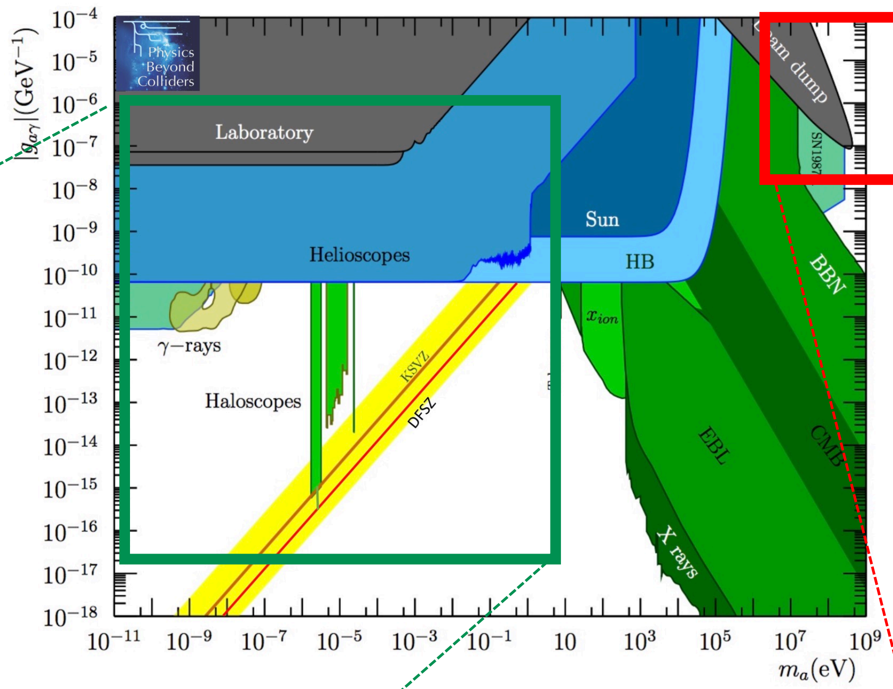
Scalar Portal: Interplay





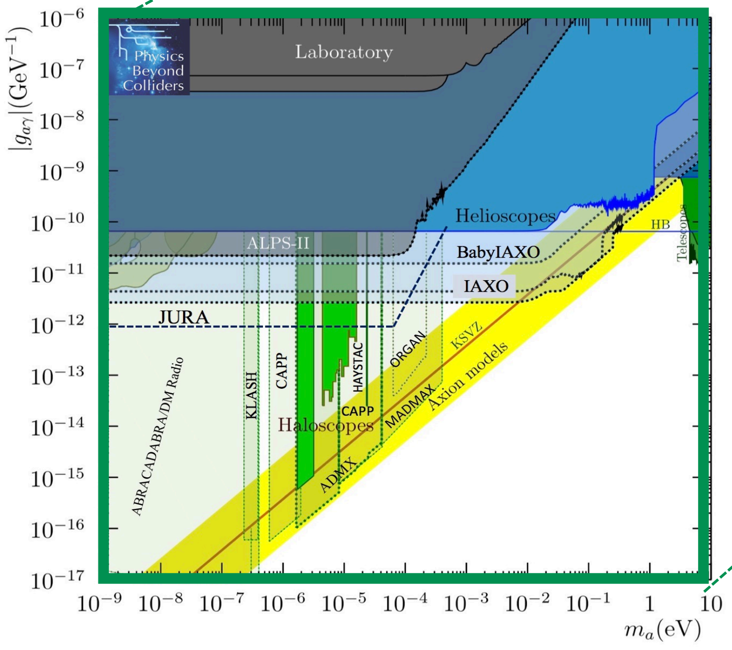


ALPs with photon coupling: coverage, complementarity, interplay

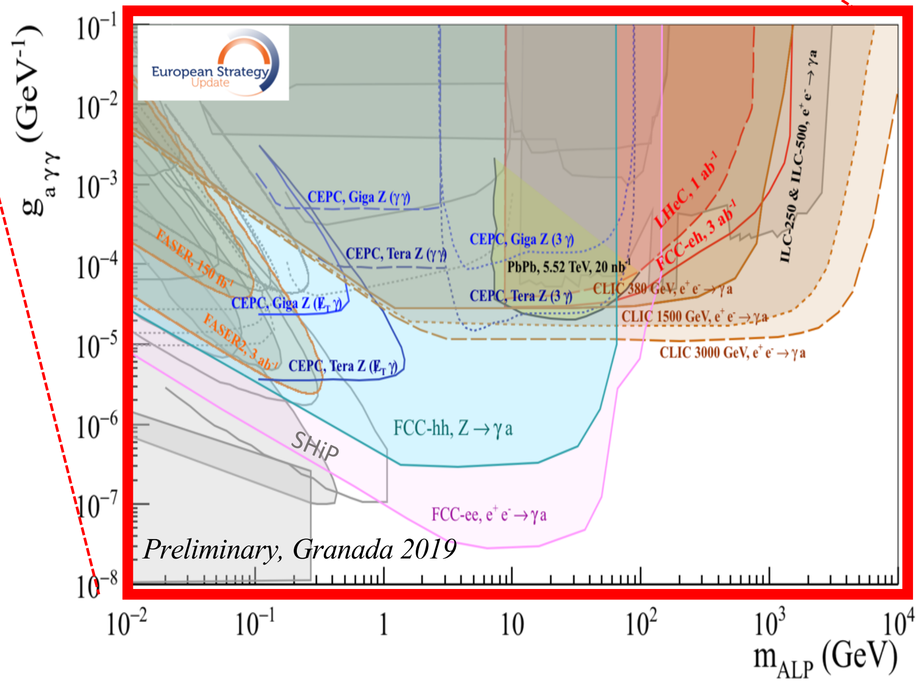


sub-eV range accessible at helioscopes and haloscopes

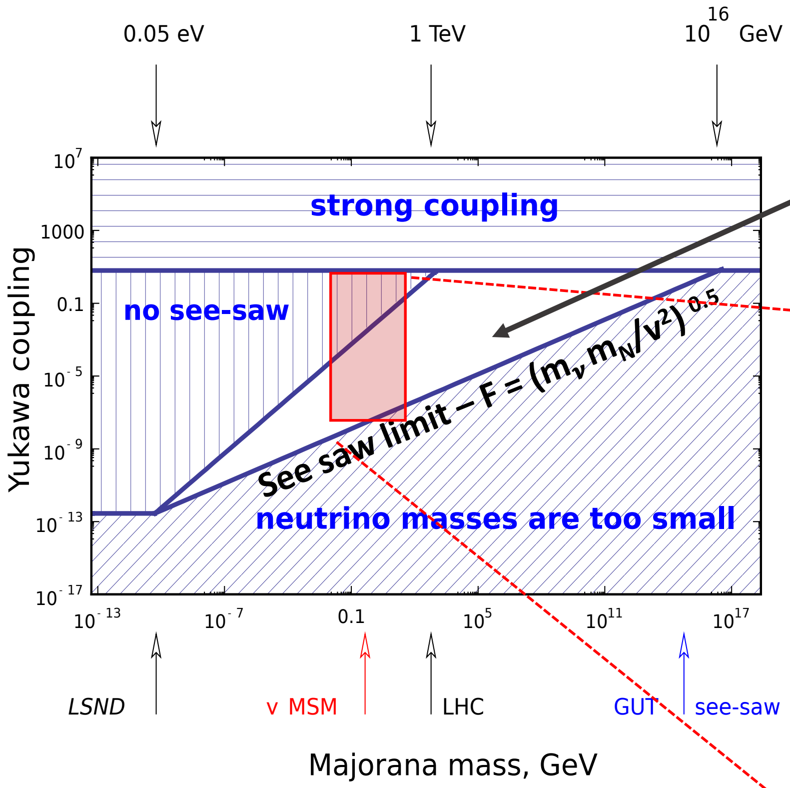
MeV-10 GeV range accessible at accelerators' based experiments



Nice complementarity of accelerator-based experiments, experiments in the sub-eV range, and cosmological bounds

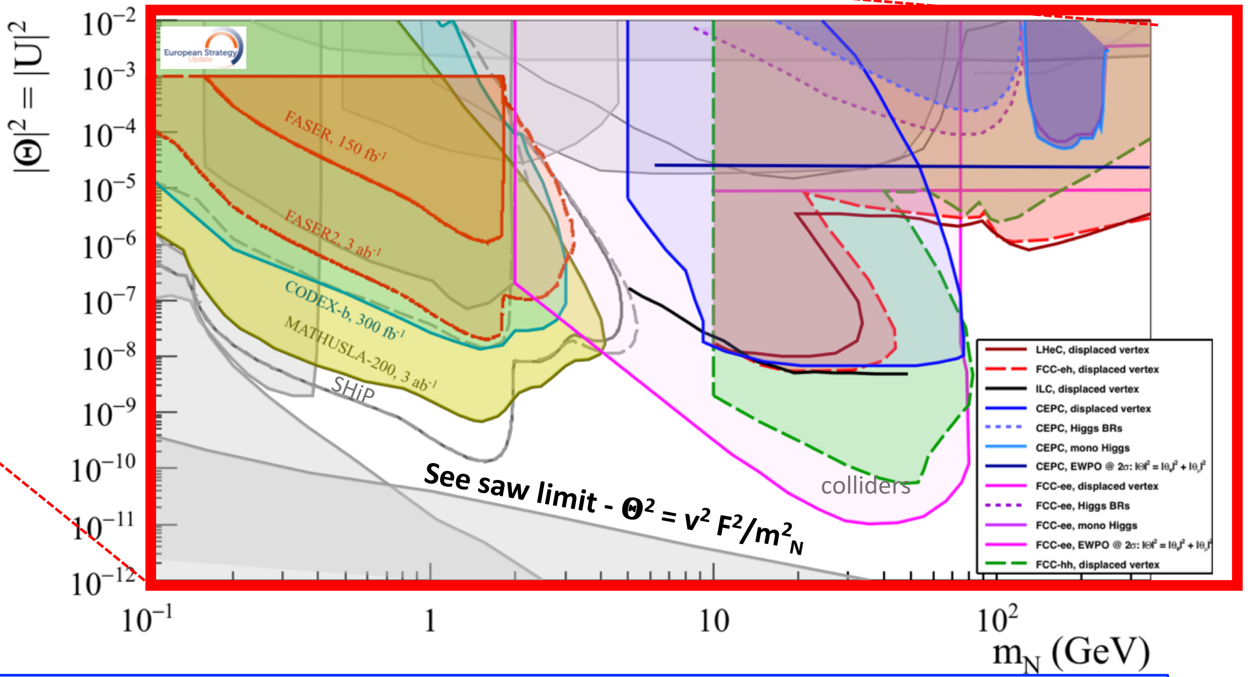


Fermion Portal: coverage, complementarity, interplay



Back to the initial plot:

SU(2)xU(1)$_L$ singlet Right Handed Neutrinos responsible of the neutrinos' mass generation can have any coupling/mass in the white area, assuming an approximate U(1)$_L$ global symmetry.

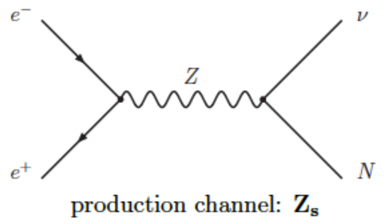


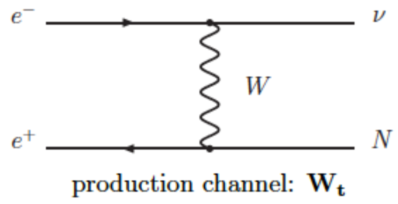
With beam dump and future colliders's experiments we can explore (light) RHN in the mass range 0.1-90 GeV almost down to the see-saw limit.

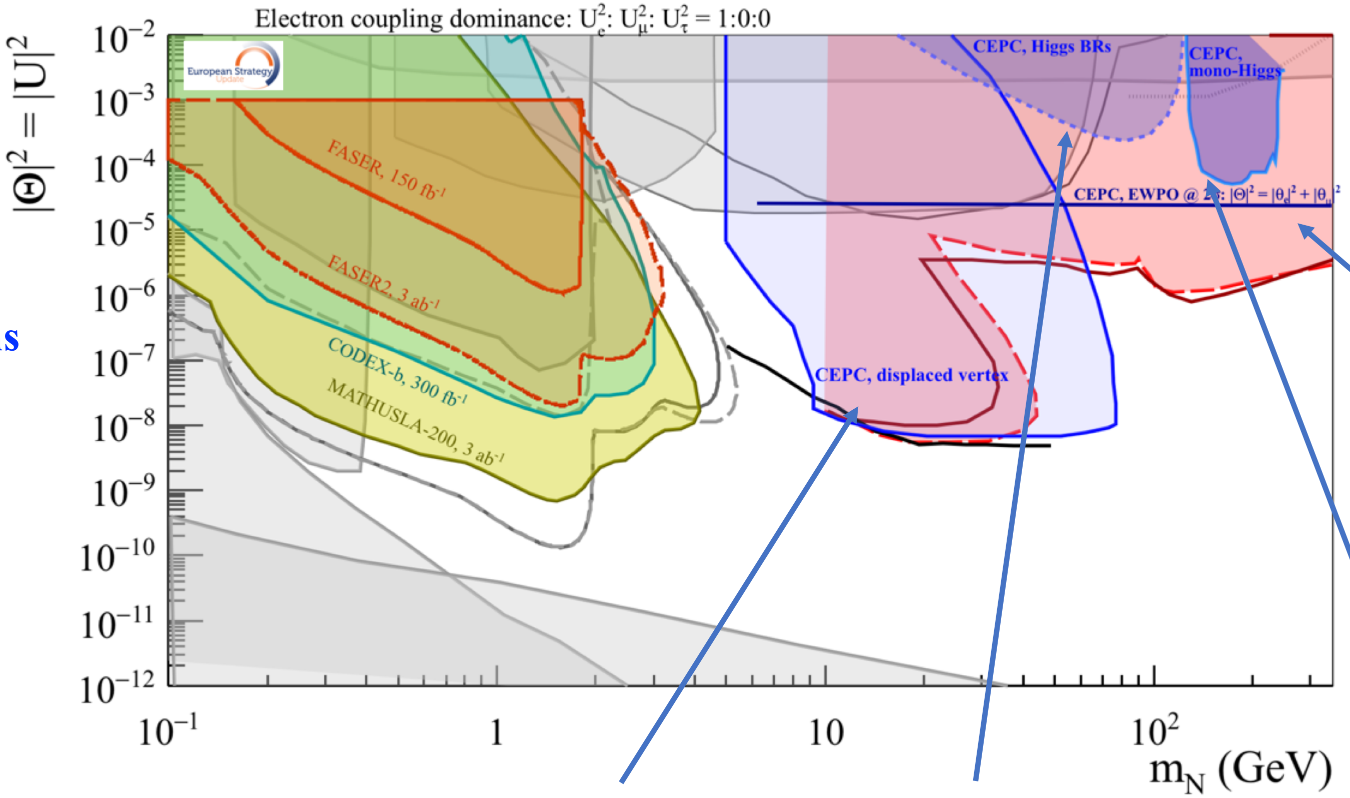
Inverse problem: Fermion Portal

Prospects for CEPC: 10 ab^{-1} at the Z-pole and 5 ab^{-1} at 240 GeV.

Production mechanisms at $e^+ e^-$ colliders:







Displaced vertex searches:
Several decay modes accessible

Higgs BR:
presence of HNL modifies the Higgs width and BRs. The more sensitive is the $H \rightarrow WW$ which constrains $H \rightarrow \nu N$ (and Θ^2)

Source:
CEPC report, arXiv: 1811.10545
Based on arXiv:1612.02728

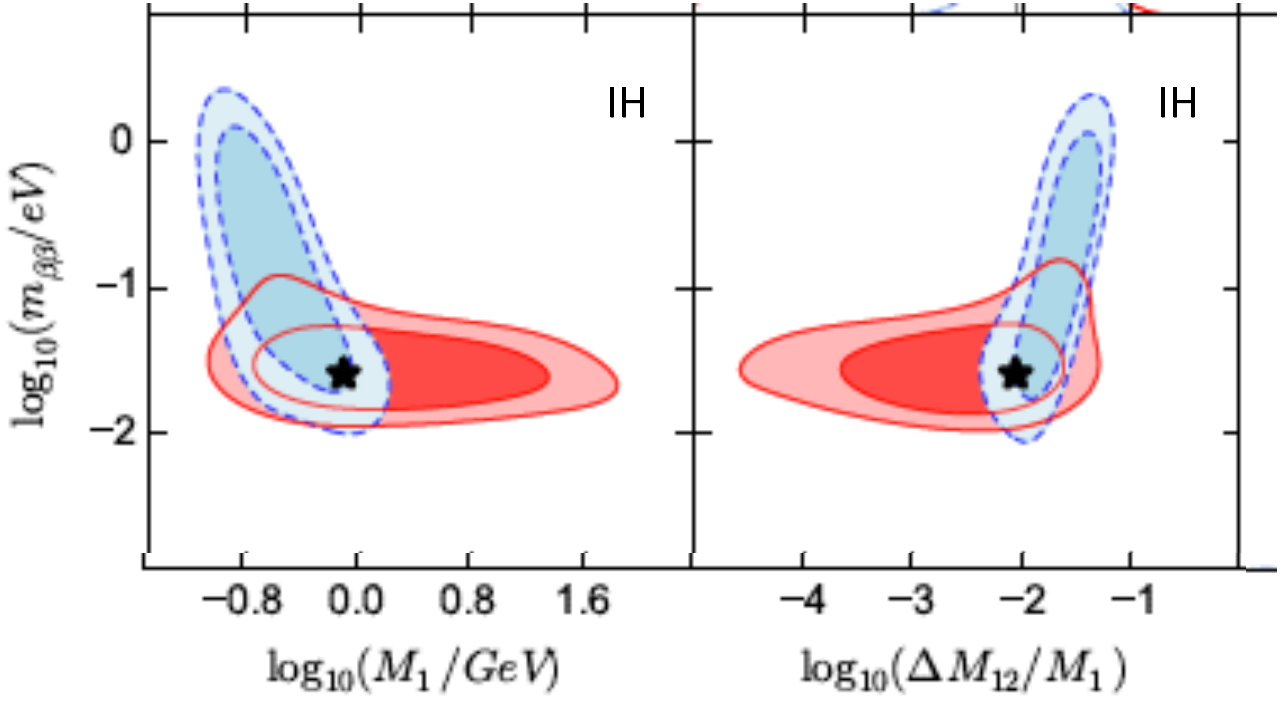
EWPO:
The PMNS matrix in presence of HNLs is not unitary. Modification of the theory prediction of precision observables. Present constraints include: EWPO, lepton universality, charged LFV, CKM unitarity

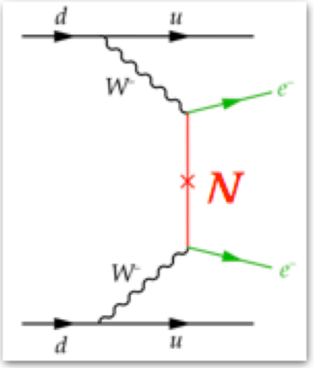
Mono-Higgs:
if m_N is above the Higgs mass,
$N \rightarrow \nu\ H$, $H \rightarrow$ hadronically (dijet).

Fermion Portal: a possible connection to $0\nu\beta\beta$ decay

P. Hernandez et al, arXiv:1606.06719
See also:
Drewes, Eijima arXiv:1606.06221

Correlation of $|m_{\beta\beta}|$ and RHN mass and mass degeneracy for N=2 scenario for 68% and 90% CL contours probability for successful baryogenesis





Red contours: log M prior,
Blue contours: log DM prior

Fermion Portal: possible connection to active-neutrinos oscillation data

Antusch, Drewes et al.
arXiv:1710.03744

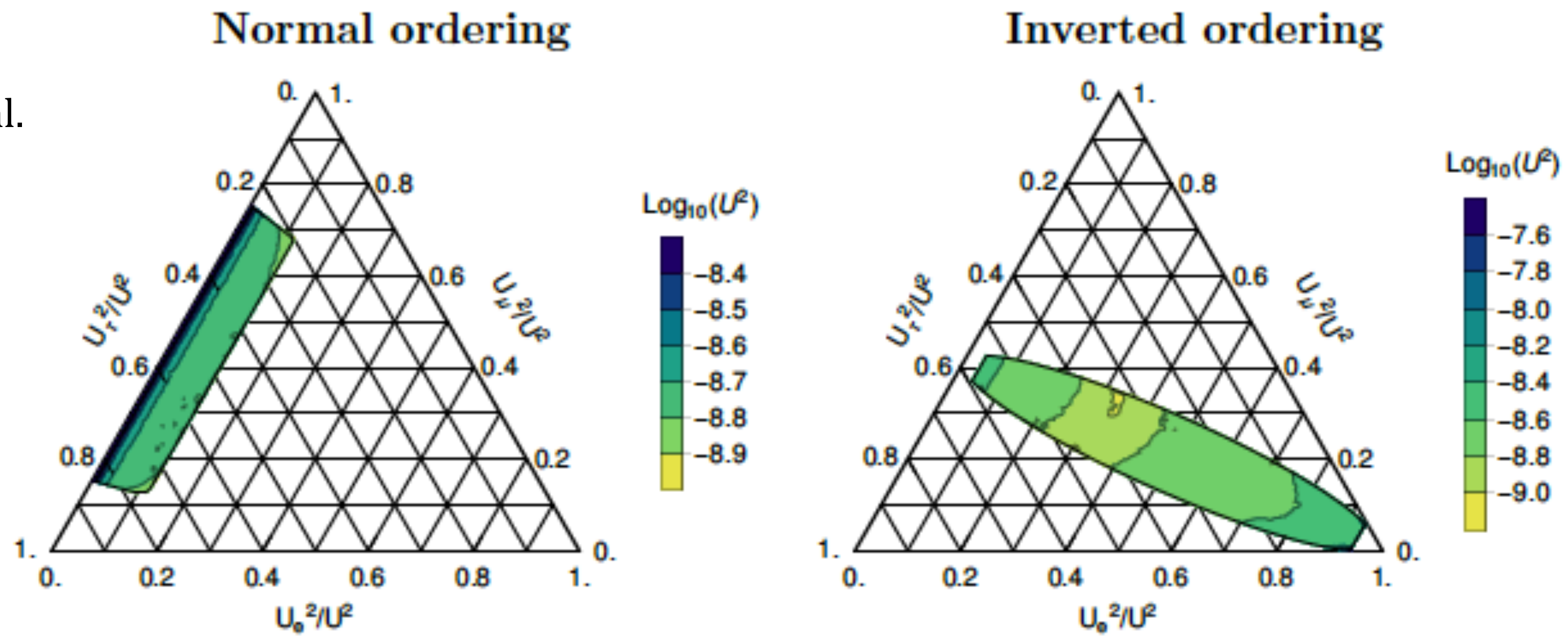


Figure 9: *The region within the black lines is allowed by light neutrino oscillation data. The colour indicates the largest mixing angle U^2 consistent with the observed BAU and seesaw constraints for the cases of normal ordering (left) and inverted ordering (right) for right-handed neutrino with an average mass $\bar{M} = 30\,\text{GeV}$. Note that the largest viable mixing angles are found in the case of a highly flavour asymmetric flavour pattern, where $U_a^2 \ll U^2$ for any of the flavours.*

SPARES

Higgs coupling fit results used by Fuchs, Schlaffer, Perez

Collider	$\sqrt{s}$ [TeV]	$\mathcal{L}_{\text{int}}$ [ab^{-1}]	BR$_{\text{NP}}$ [%]	$\delta\kappa$ [%]	Ref.
LHC1	7, 8	0.022	20	26	[14] Tab. 11
LHC3	13	0.3	12.3	8.6	
HL-LHC	14	6	4.1	1.3	[15] Tab. 5
HE-LHC	27	15	2.6	0.8	
LHeC	1.3	1	1.6	0.4	
ILC250	0.25	2	1.6	0.34	[16] Tab. XIX
ILC500	0.25, 0.35, 0.5	2+0.2+4	1.2	0.28	
CEPC	$M_Z, 2M_W, 0.24$	16+2.6+5.6	1.1	0.24	[15] Tab. 5
FCCee240	0.24	5	1.2	0.26	[15] Tab. 5
FCCee365	0.365	1.7	1.1	0.24	
FCCee/eh/hh	100	30	1	0.21	[17] Tab. 5
TeraZ	M_Z	$N_Z = 10^{12}$			
CLIC stage 1	0.38	1	0.92	0.4	[18] Tab. 6c
CLIC stage 2	1.5	2.5	0.39	0.2	
CLIC stage 3	3	5	0.26	0.1	

Table 1. Pre-arXiv version: Bounds in the $\kappa - 3$ scenario on the BR$_{\text{NP}}$ and uncertainty in the determination of the most precise κ (namely κ_Z except for CLIC stage 2 and 3 and LHeC where κ_W is more precise) at different benchmarks of the LHC and future lepton colliders with given energy and luminosity. Assumptions on the polarization can be found in the original references. The LHC Run-3 bound at approximately 95% CL was obtained by multiplying the 68% CL bound from Ref. [14] by the ratio of the quantiles of a χ^2 distribution with 2 parameters assuming that a true 2-parameter (BR$_{\text{NP}}$ and one global κ) fit will be dominated by the most precise κ.

[14] P. Bechtle, S. Heinemeyer, O. Stl, T. Stefaniak and G. Weiglein, *Probing the Standard Model with Higgs signal rates from the Tevatron, the LHC and a future ILC*, *JHEP* **11** (2014) 039, [1403.1582].

[15] J. de Blas et al, *Ecfa: Higgs boson studies at future particle colliders, confidential version from 5/5/2019*, 2019.

[16] P. Bambade et al., *The International Linear Collider: A Global Project*, 1903.01629.

[17] J. de Blas et al, *Ecfa: Higgs boson studies at future particle colliders, confidential version from 9/5/2019*, 2019.

[18] J. de Blas et al., *The CLIC Potential for New Physics*, 1812.02093.

[19] J. de Blas et al., *Higgs Boson Studies at Future Particle Colliders*, 1905.03764.

Higgs Boson studies at future particle colliders

arXiv:1905.03764

kappa-3 scenario	HL-LHC	HL-LHC + LHeC	HL-LHC + HE-LHC
κ_W (%, ≤ 1)	−1.7	−0.3	−0.8
κ_Z (%, ≤ 1)	−1.3	−0.7	−0.7
κ_g (%)	±2.2	±1.6	±1.1
κ_γ (%)	±1.7	±1.5	±0.82
$\kappa_{Z\gamma}$ (%)	±10.	±11. ⋆	±3.7
κ_c (%)	–	±3.7	–
κ_t (%)	±2.8	±2.7 ⋆	±1.6
κ_b (%)	±2.6	±1.2	±1.4
κ_μ (%)	±4.4	±4.4 ⋆	±1.7
κ_τ (%)	±1.6	±1.3	±0.87
BR_{inv} (<%, 95% CL)	1.9	1.1	1.5 ∗
BR_{unt} (<%, 95% CL)	inferred using constraint $\|\kappa_V\| \leq 1$ 4.1	1.3	2.2

Table 4. Expected relative precision (%) of the κ parameters in the kappa-3 scenario

kappa-3 scenario	HL-LHC+								
	ILC_{250}	ILC_{500}	$CLIC_{380}$	$CLIC_{1500}$	$CLIC_{3000}$	CEPC	FCC-ee$_{240}$	FCC-ee$_{365}$	FCC-ee/eh/hh
κ_W (%)	1.1	0.29	0.75	0.4	0.38	0.95	0.95	0.41	0.2
κ_Z(%)	0.29	0.23	0.44	0.39	0.39	0.18	0.19	0.17	0.17
κ_g(%)	1.4	0.84	1.5	1.1	0.86	1.1	1.2	0.89	0.53
κ_γ (%)	1.3	1.2	1.5∗	1.3	1.1	1.2	1.3	1.2	0.36
$\kappa_{Z\gamma}$ (%)	11.∗	11.∗	11.∗	8.4	5.7	6.3	11.∗	10.∗	0.7
κ_c (%)	2.	1.2	4.1	1.9	1.4	2.	1.6	1.3	0.97
κ_t (%)	2.7	2.4	2.7	1.9	1.9	2.6	2.6	2.6	0.95
κ_b (%)	1.2	0.57	1.2	0.61	0.53	0.92	1.	0.64	0.48
κ_μ (%)	4.2	3.9	4.4∗	4.1	3.5	3.9	4.	3.9	0.44
κ_τ (%)	1.1	0.64	1.4	0.99	0.82	0.96	0.98	0.66	0.49
BR_{inv} (<%, 95% CL)	0.26	0.22	0.63	0.62	0.61	0.27	0.22	0.19	0.024
BR_{unt} (<%, 95% CL)	1.8	1.4	2.7	2.4	2.4	1.1	1.2	1.	1.

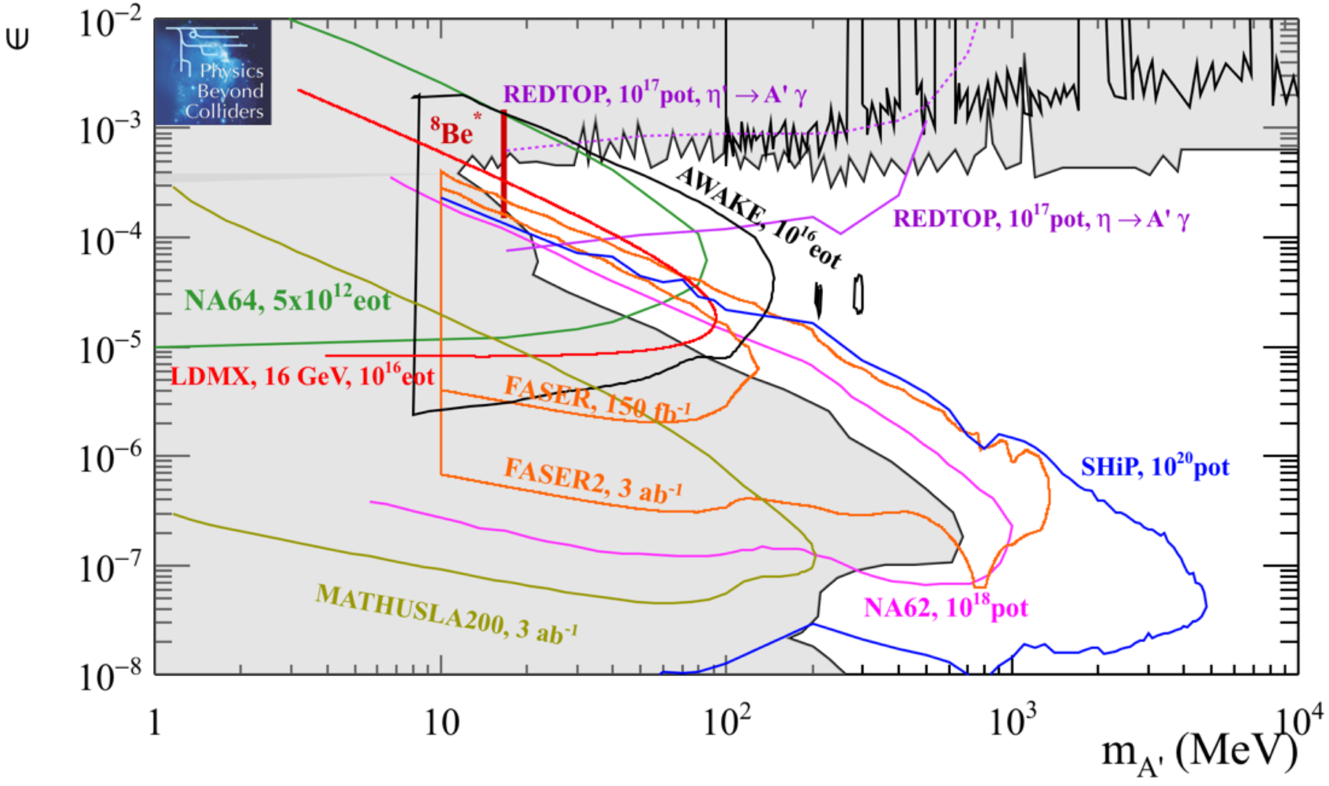
Table 5. Expected relative precision (%) of the κ parameters in the kappa-3 (combined with HL-LHC) scenario

Vector portal
(Dark Photons)

$$-\frac{\varepsilon}{2\cos\theta_W} F'_{\mu\nu} B^{\mu\nu}$$

Relevant plots from official reports/papers

Dark Photon coupled to SM particles: MATHUSLA, FASER, beam dumps



Source:
CERN-PBC-REPORT-2018-007
arXiv: 1901.09966

Figure 20: Future upper limits at 90 % CL for Dark Photon in visible decays in the plane mixing strength ϵ versus mass $m_{A'}$ for PBC projects on a ~ 10-15 year timescale. The vertical red line shows the allowed range of $e - X$ couplings of a new gauge boson X coupled to electrons that could explain the ^{8}Be anomaly [70, 71].

Dark Photon coupled to SM particles: LHCb (Run3++)

Source:
Beyond the Standard Model Physics
at the HL-LHC and HE-LHC – arXiv:1812.07831

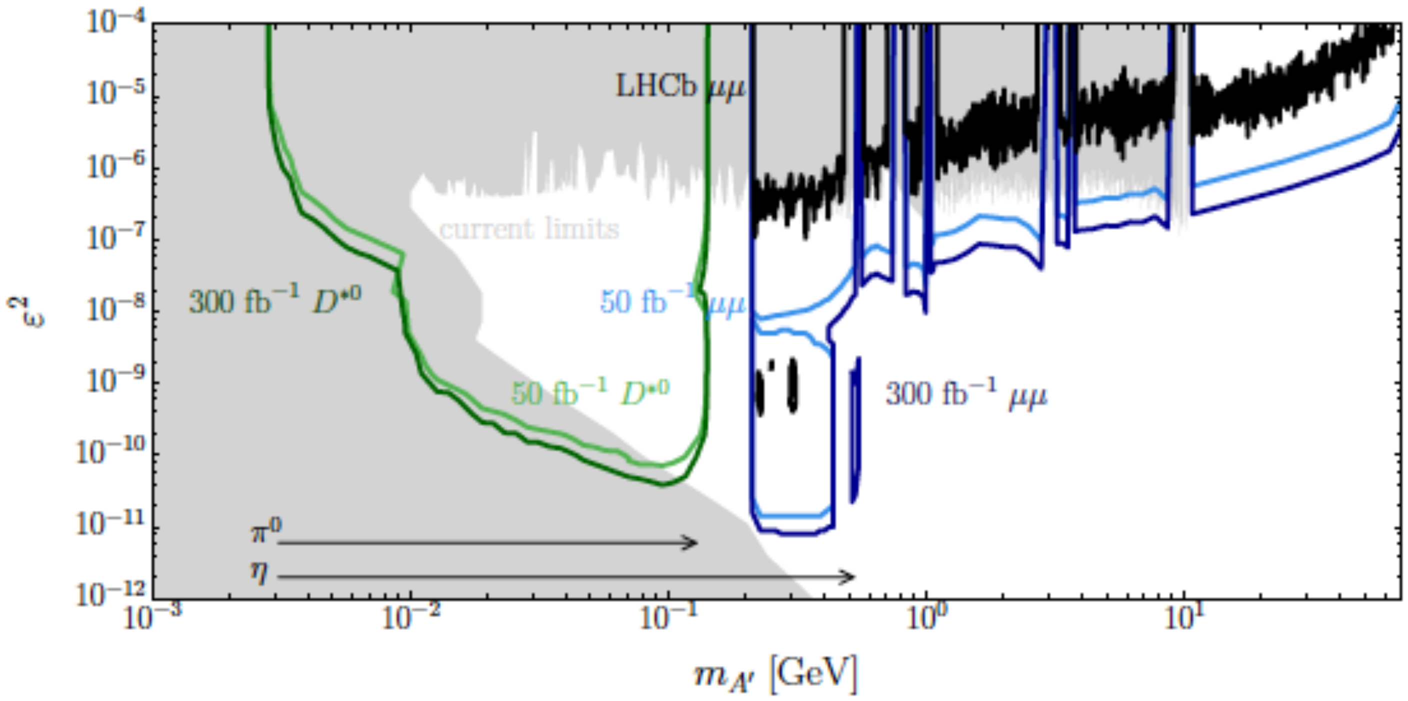


Fig. 3.4.1: Current limits (grey fills), current LHCb limits (black band), and proposed future experimental reach (coloured bands) on A' parameter space. The arrows indicate the available mass range from light meson decays into $e^+e^-\gamma$.

Dark Photon coupled to SM particles: CEPC

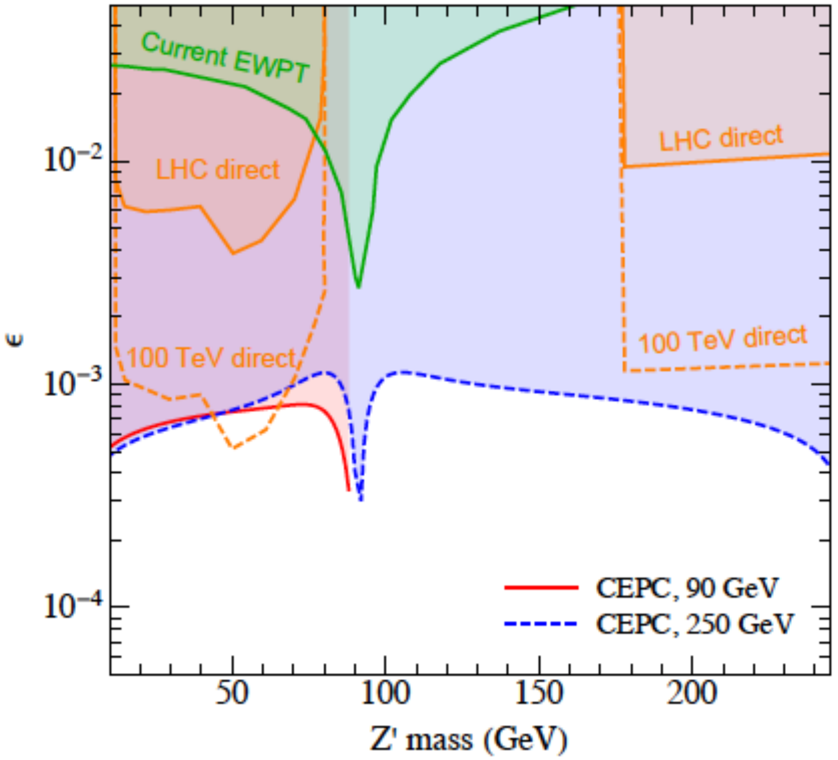


Figure 2.25: This figure illustrates CEPC's capacity to probe dark photons via radiative return. The red-solid and blue-dashed lines show the 95% CL projected sensitivity to the (hypercharge) mixing parameter, ϵ, as a function of the dark photon's mass, $m_{Z'}$. The red curve corresponds to $\sqrt{s} = 90$ GeV and $\mathcal{L} = 0.5\ \text{ab}^{-1}$ while the blue curve shows 250 GeV and 5 ab^{-1}. The figure is adapted from Refs. [190, 191].

Source:
The CEPC Conceptual Design Report, Vol II: Physics and Detector, arXiv: 1811.10545

Dark Photon coupled to SM particles: FCC-ee

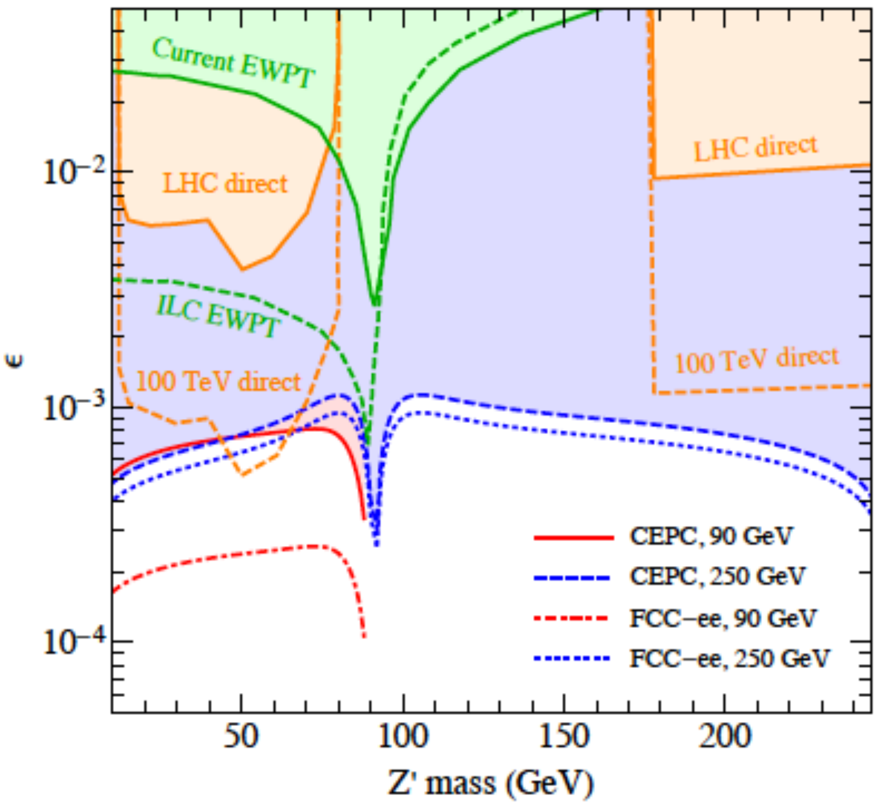


Figure 8: Dark photon limits at 95% C.L. on the hypercharge mixing ϵ as a function of dark photon mass. The $\sqrt{s} = 90$ GeV and 250 GeV lines show our projections with future e^+e^- colliders with integrated luminosities specified in Table I. Electroweak precision constraints (EWPT) and direct searches are taken from [42]. The 100 TeV projection assumes an integrated luminosity of 3000 fb^{-1}.

Source: Rosner et al., 1503.07209 approved by the FCC-ee contact person.

Comments:
FCC-ee curves at 250 GeV use 10 ab^{-1} (instead of 5 ab^{-1}) while at 90 GeV assume 10^{12} Z (instead of 5×10^{12} Z)

Dark Photon coupled to SM particles: FCC-hh (100 TeV)

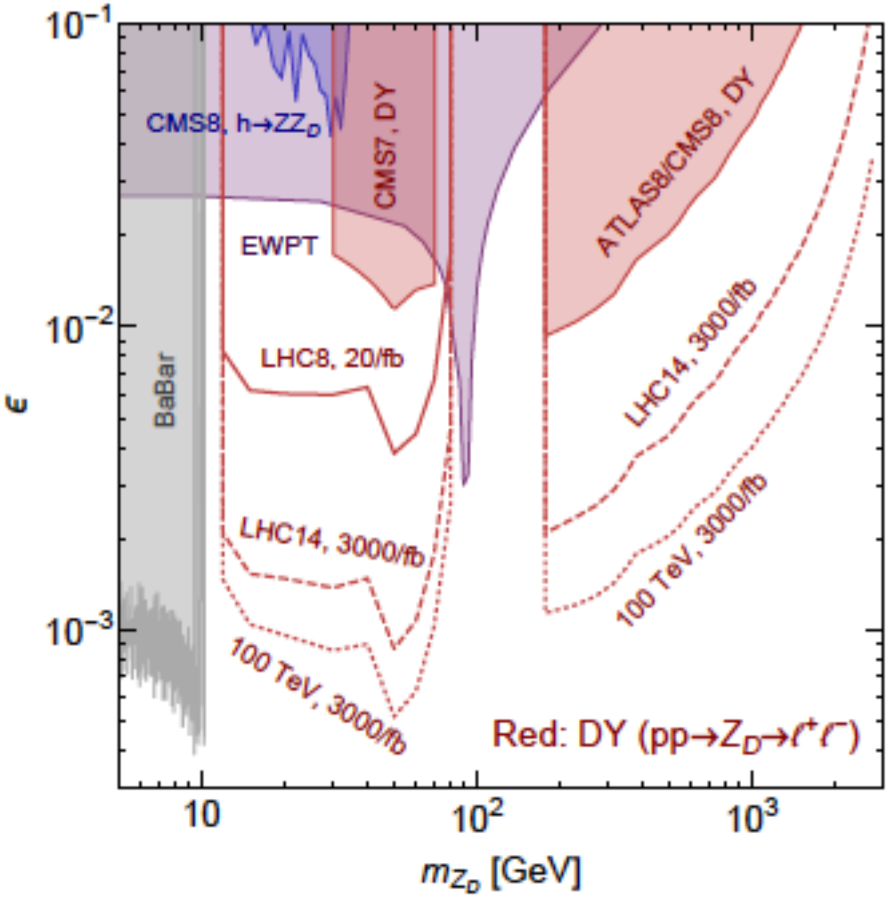
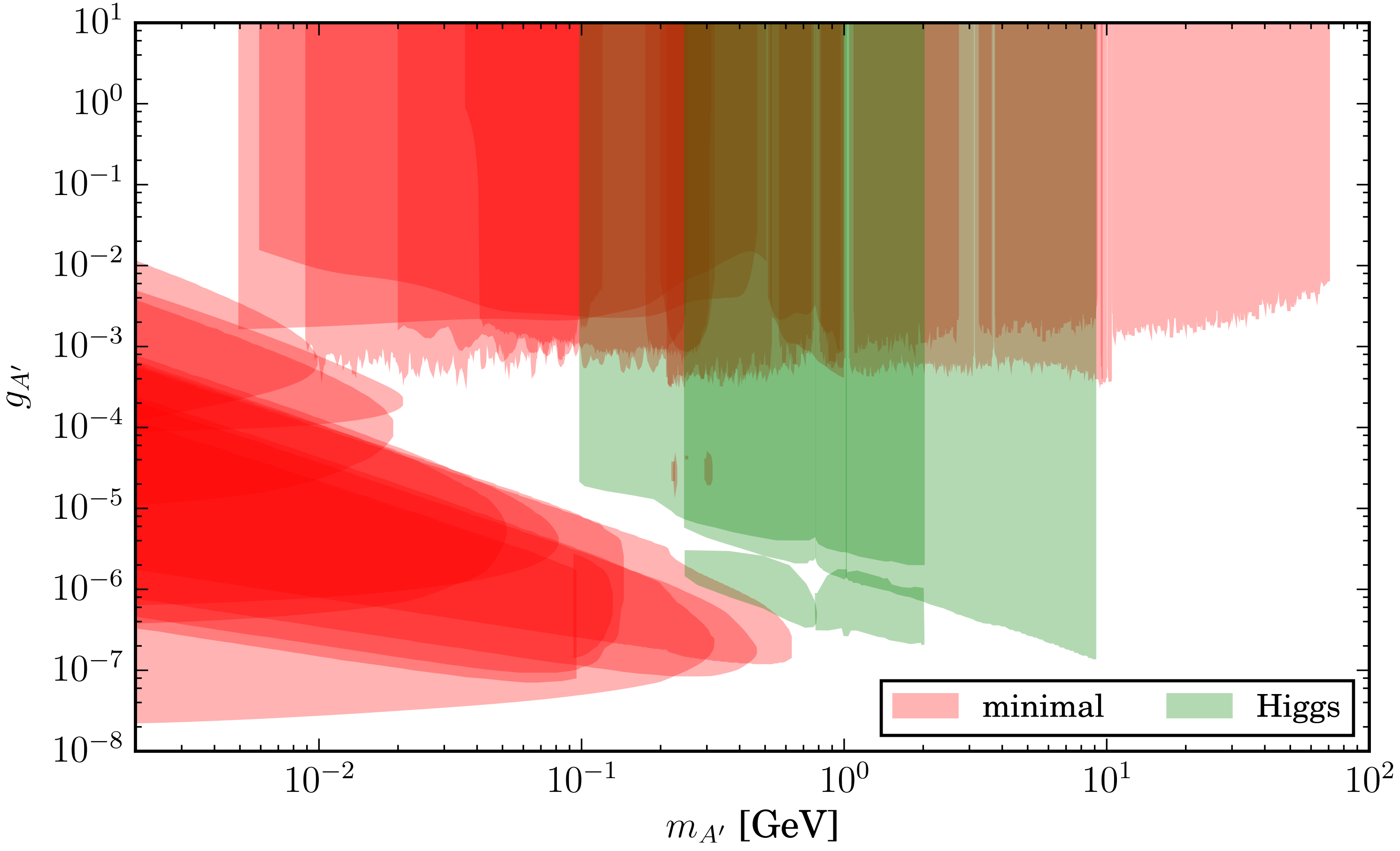


Figure 8. Prospects for Z_D searches from DY production (red lines) at LHC8 (20 fb^{-1}, solid), LHC14 (3000 fb^{-1}, dashed), and a 100 TeV pp collider (3000 fb^{-1}, dotted), with limits from existing recasts shown in shaded red (from [71, 72, 136, 137] and our rescalings, see text for details). A recast [67] of a CMS8 analysis [122] sensitive to $h \to ZZ_D$ is shown in the blue shaded region. The purple region shows the current EWPT constraints (this work, see Sec. 3), while the gray region is a limit from BaBar [61].

Source: D. Curtin et al., arXiv: 1412.0018
Approved by the FCC-hh contact person.

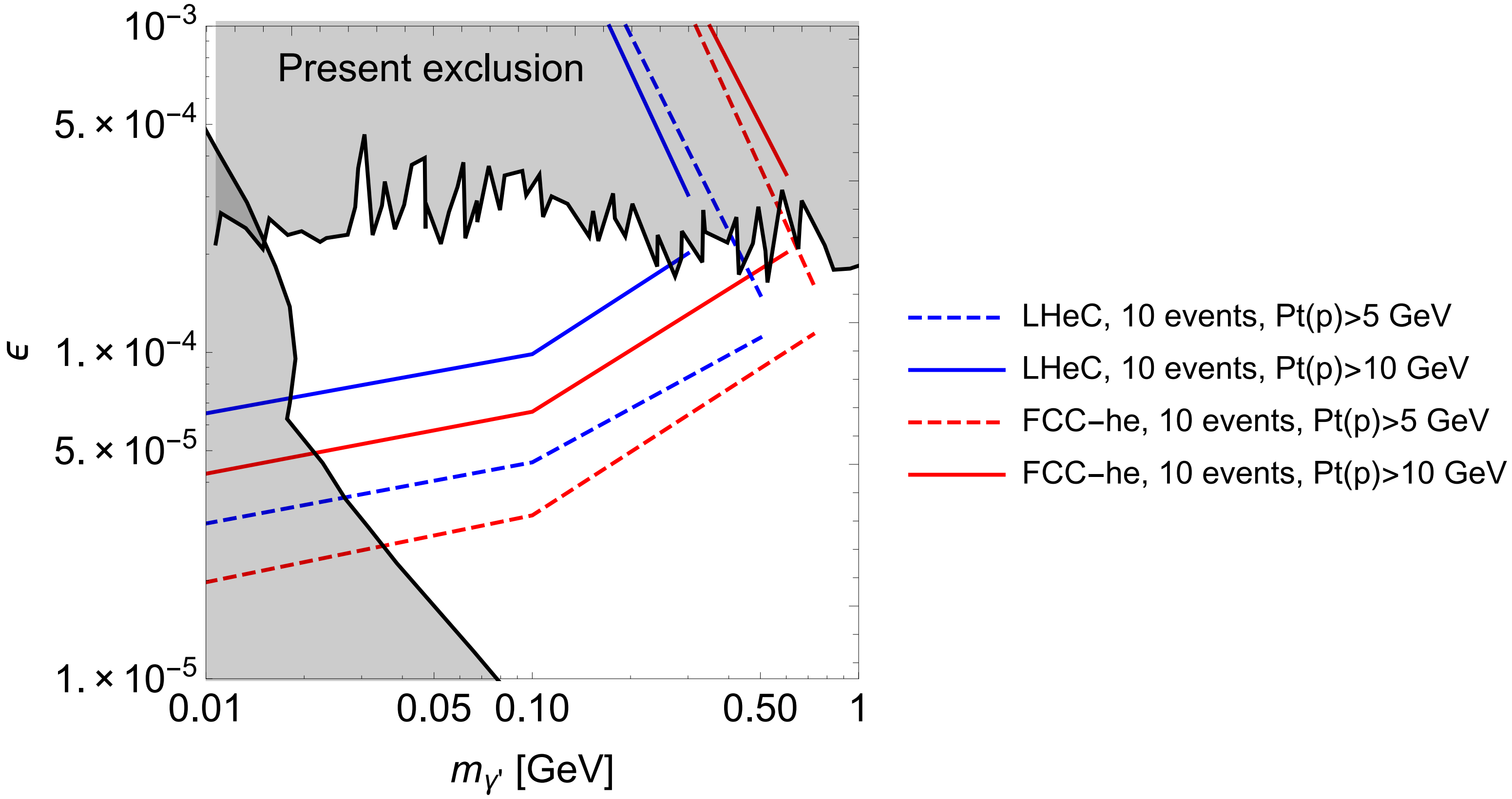
Dark Photon coupled to SM particles: HL-LHC



Source:

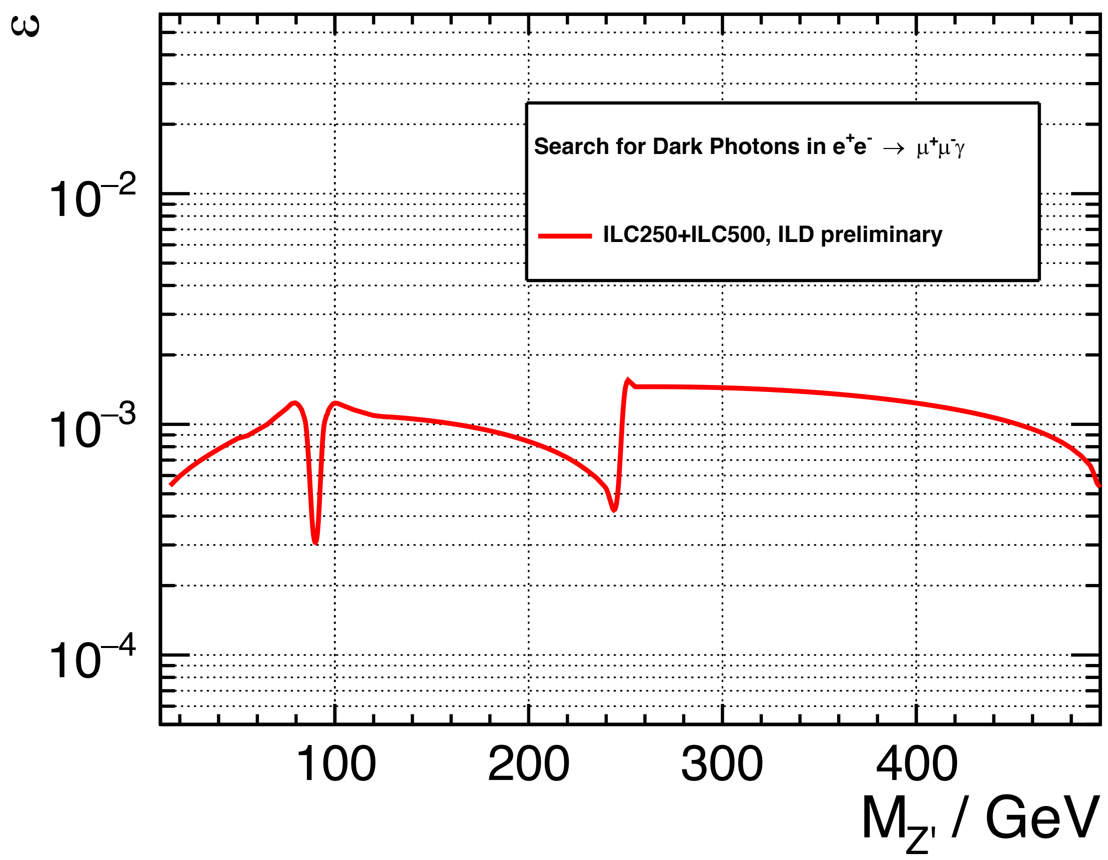
Beyond the Standard Model Physics
at the HL-LHC and HE-LHC – arXiv:1812.07831

Dark Photon coupled to SM particles: LHeC and FCC-eh



Plot provided by O. Fischer for the Granada Symposium.

Dark Photon coupled to SM particles: ILC



Plot provided by M. Peskin for the Granada Symposium.

Scalar portal
(Dark Scalar/relaxion)

$$(\mu S + \lambda\, S^2) H^\dagger H$$

Relevant plots from official reports/papers

Dark Scalar/relaxion coupled to the Higgs:
MATHUSLA, FASER, CODEX-b, LHCb (and beam dump exps)

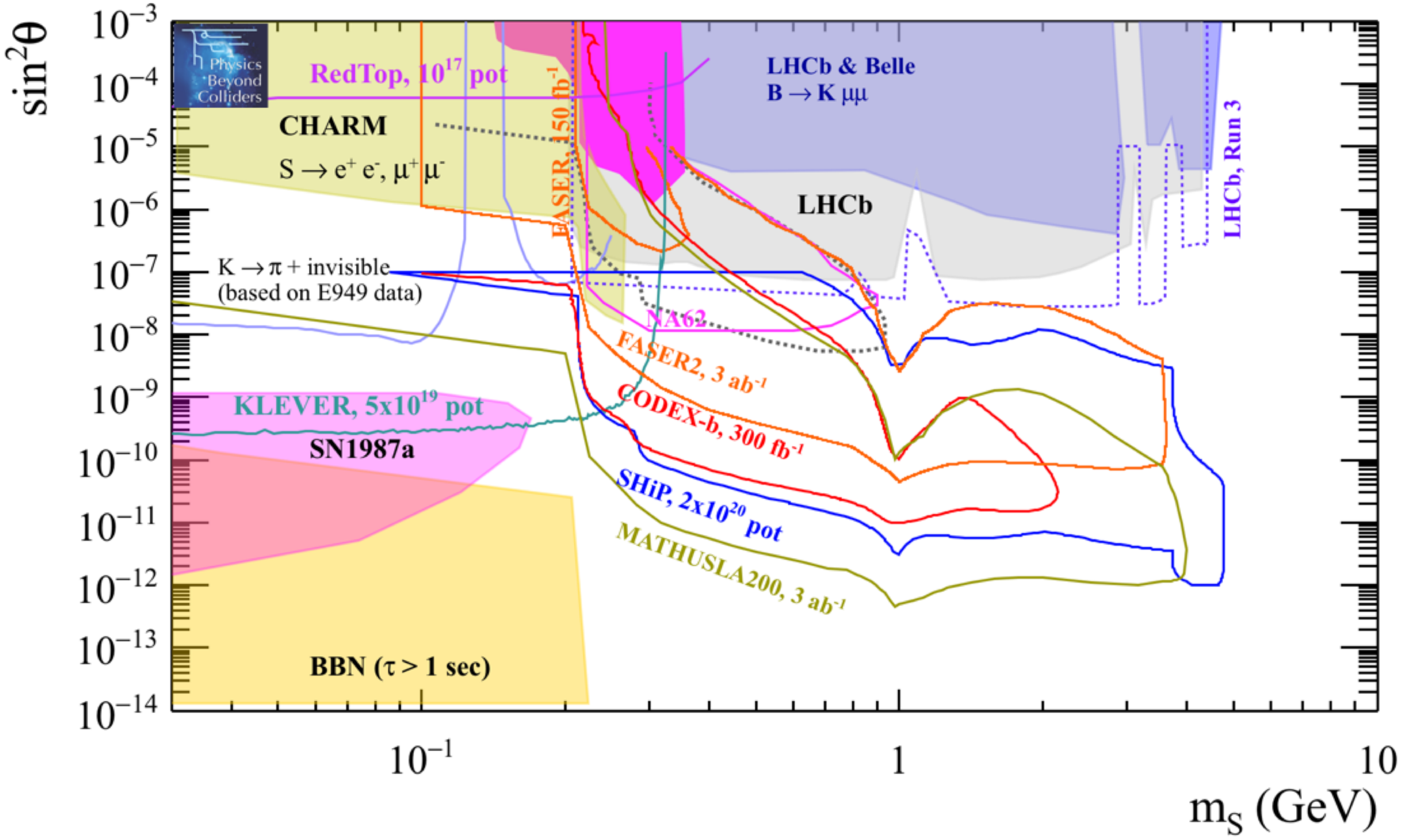


Figure 28: BC4: prospects on 10-15 year timescale for PBC projects for the Dark Scalar mixing with the Higgs in the plane mixing angle $\sin^2\theta$ versus dark scalar mass m_S.

Source: PBC-BSM report
arXiv:1901.09966
(λ = 0)

Dark Scalar/relaxion coupled to the Higgs:
MATHUSLA, FASER, CODEX-b, LHCb (and beam dump exps)

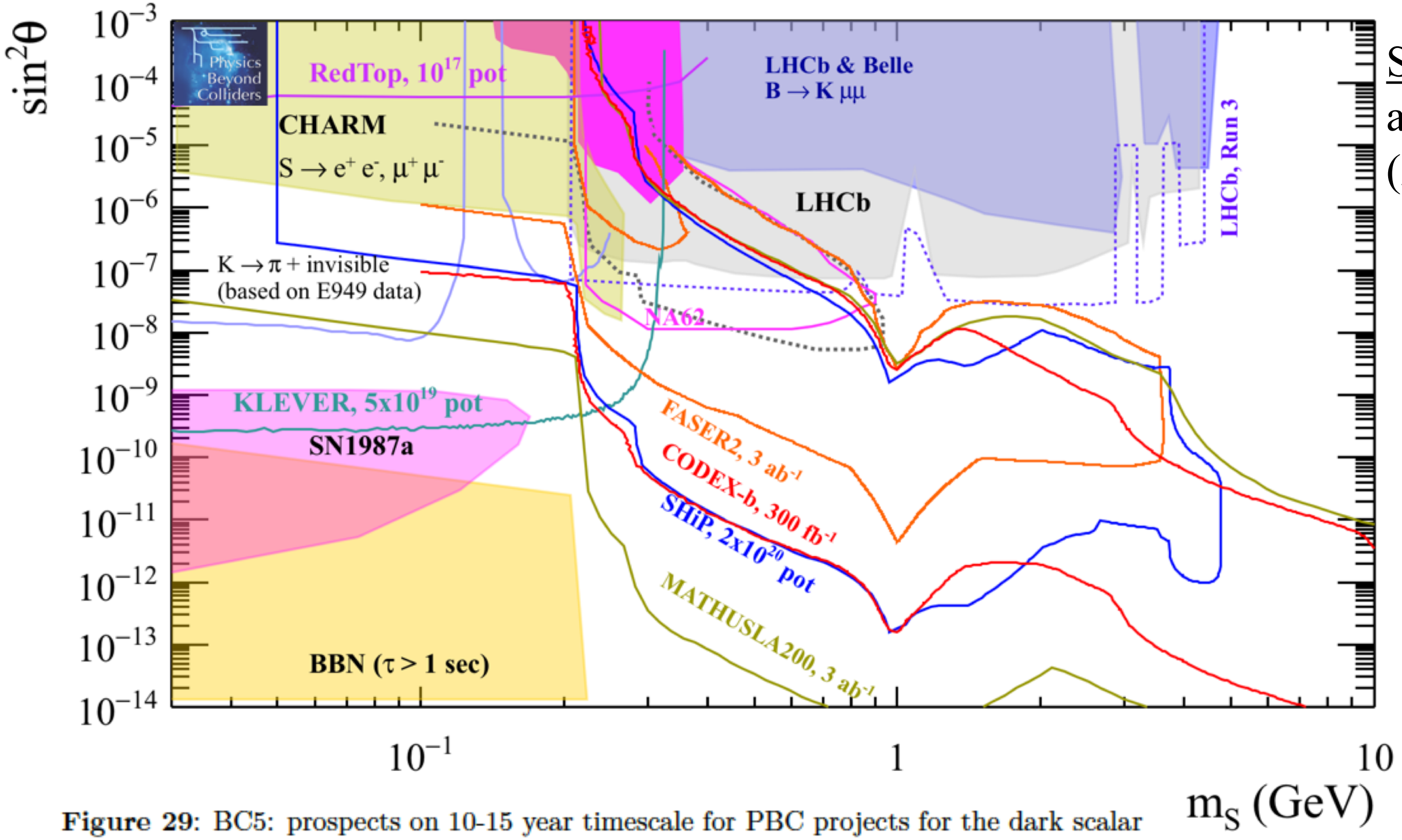


Figure 29: BC5: prospects on 10-15 year timescale for PBC projects for the dark scalar mixing with the Higgs in the plane mixing angle $\sin^2\theta$ versus dark scalar mass m_S under the hypothesis that both parameters λ and μ are different from zero. The sensitivity curves have been obtained assuming $BR(h \to SS) = 10^{-2}$. The NA62^{++} and KLEVER curves correspond still to the case of $\lambda = 0$, and, hence, should be considered conservative.

Source: PBC-BSM report
arXiv:1901.09966
($\lambda \sim 4 \times 10^{-3}$)

Pseudo-scalar portal
Axions/ALPs with photon couplings

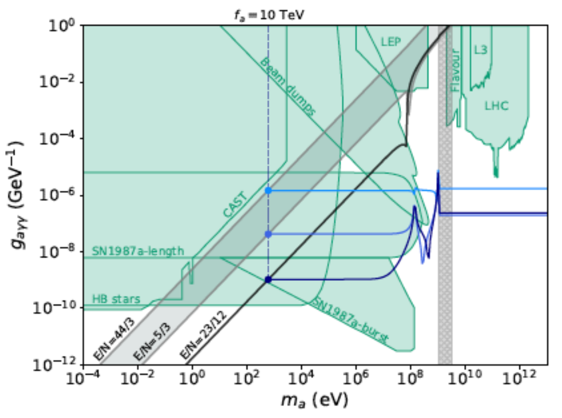
$$\frac{a}{f_a} \tilde{F}_{\mu\nu} F^{\mu\nu}$$

Relevant plots from official reports/papers

Axions and ALPs with photon coupling: current limits at colliders

Source: arXiv:1808.10323
Bauer, Neubert, Thamm

Gavela,
1811.05466



(a) Coupling to photons.

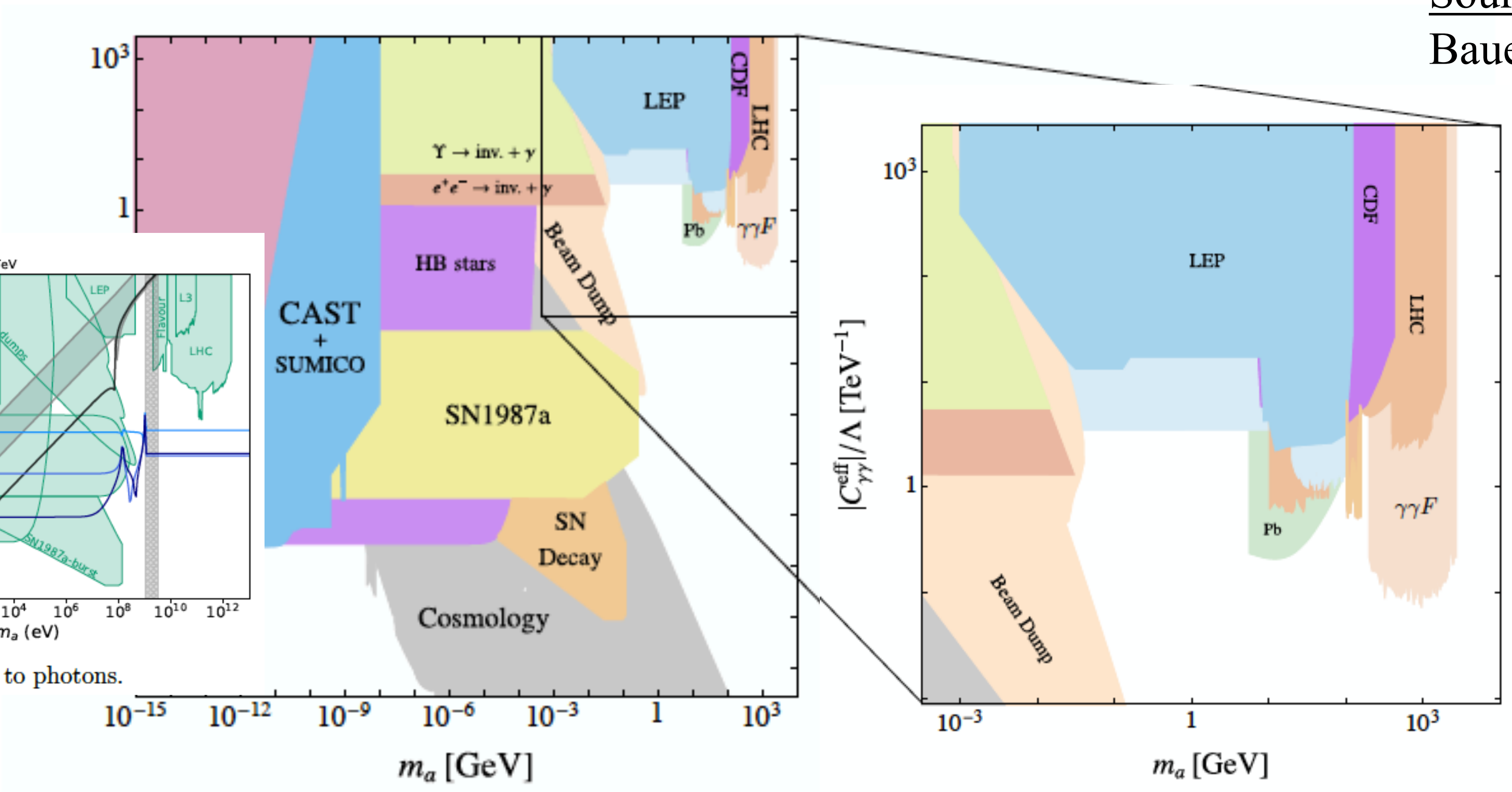
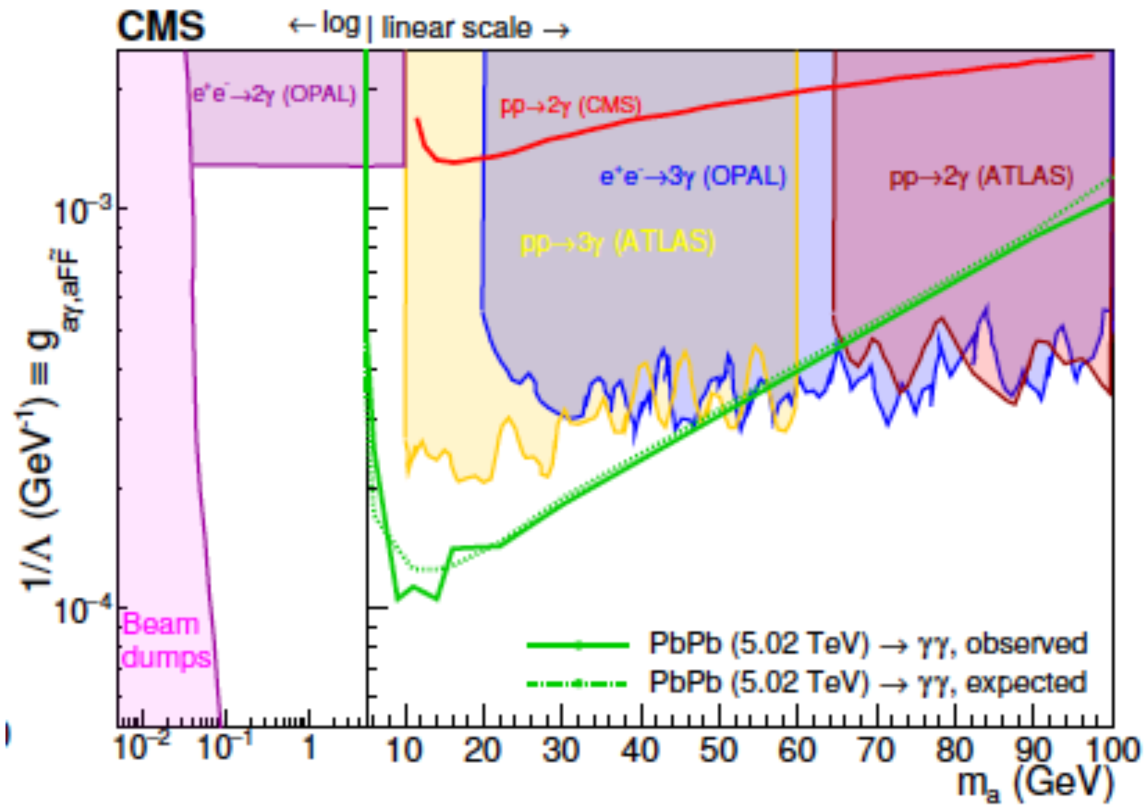


Figure 4: Left: Summary plot of constraints on the parameter space spanned by the ALP mass and ALP-photon coupling. Right: Enlarged display of the constraints from collider searches: LEP (light blue and blue), CDF (purple), LHC from associated production and Z decays (orange), LHC from photon fusion (light orange), and from heavy-ion collisions at the LHC (green).

Axions and ALPs with photon coupling: Heavy-ions limits



Right: Current 95% CL exclusion limits in the ALP-γ coupling vs. ALP mass plane [19, 20].

Source:

New Physics in Heavy Ions collisions

ESPP input # 151 and references therein

Axions and ALPs with photon coupling: FASER, MATHUSLA, BELLE-II,…

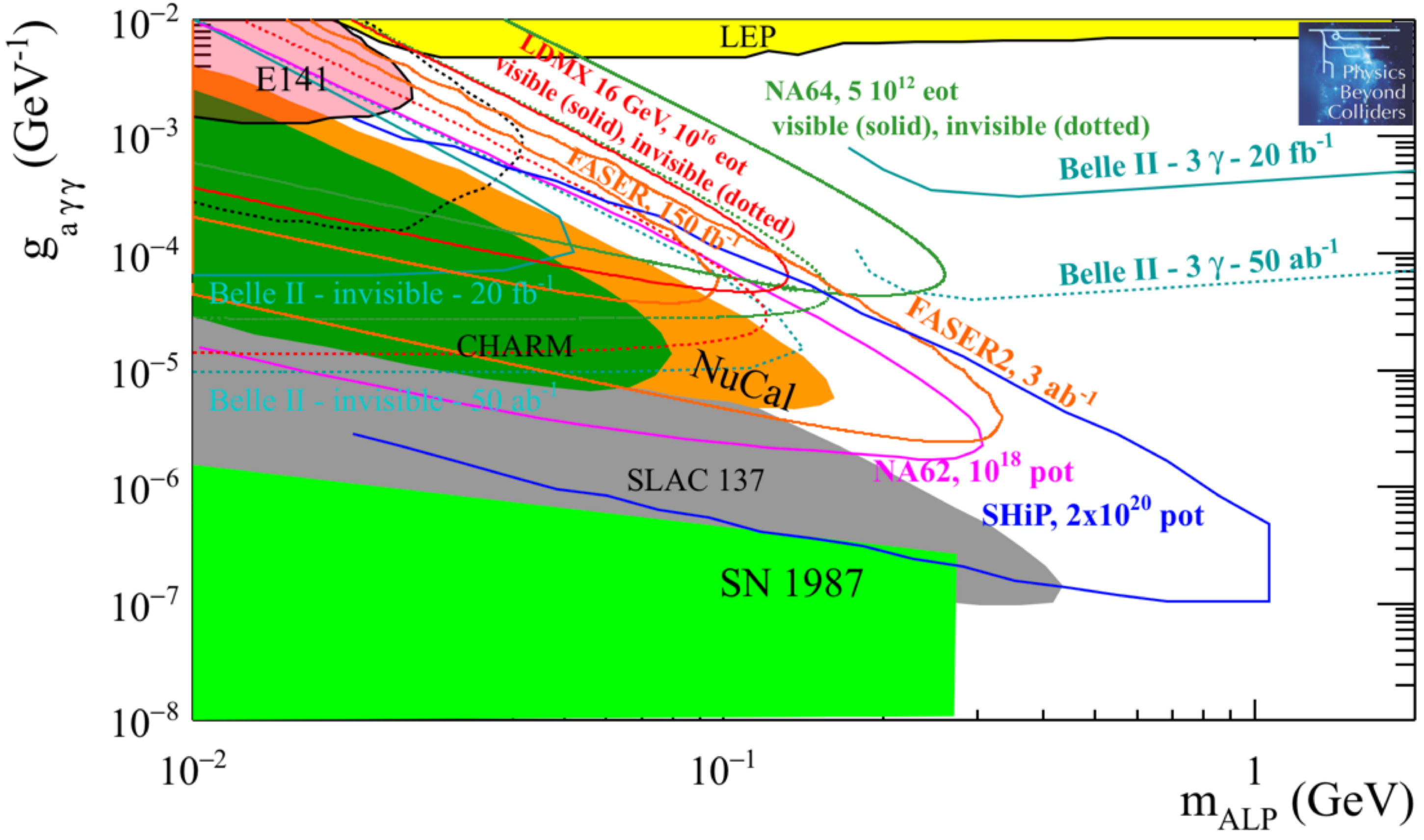
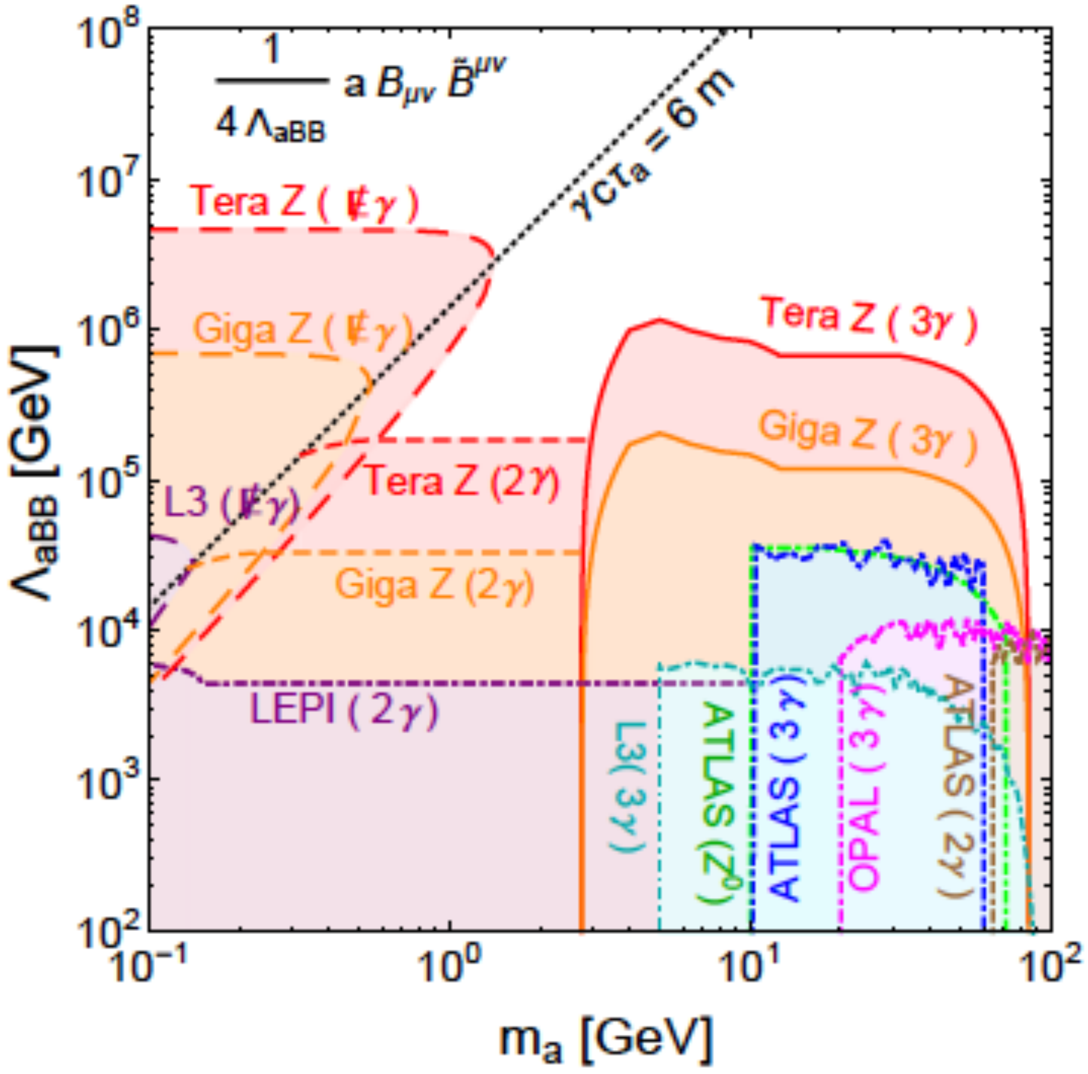


Figure 38: BC9: ALPs with photon coupling. Current bounds (filled areas) and prospects for PBC projects on 10-15 years timescale (solid lines) in the plane coupling $g_{a\gamma\gamma}$ versus mass m_{ALP}. The results from a phenomenological study for Belle-II [304] is also shown.

Source: PBC-BSM report arXiv:1901.09966

Axions and ALPs with photon coupling: CEPC

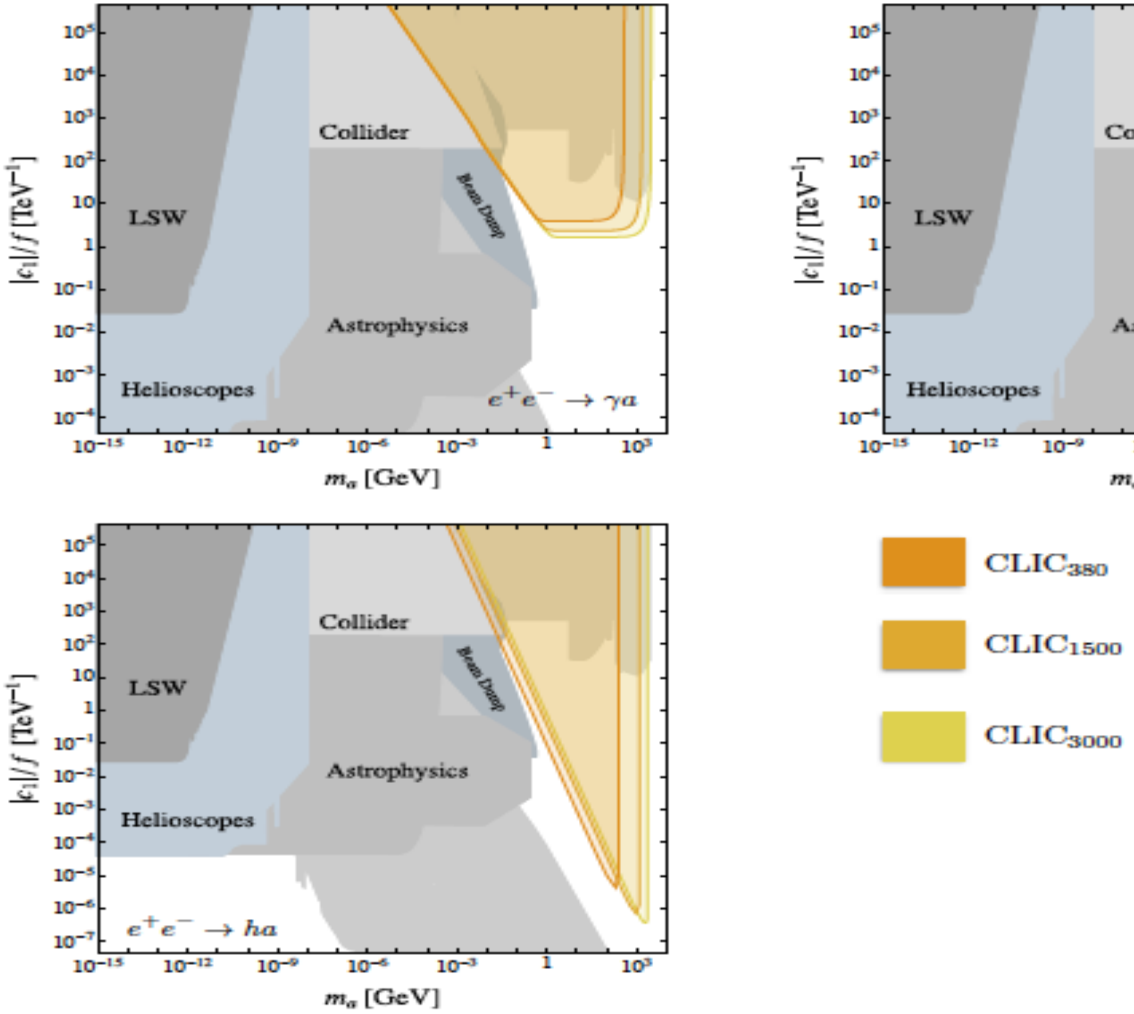


Source:

CEPC physics case, 1811.10545

Figure 2.20: The reach for rare Z decays at CEPC in two benchmark scenarios, adapted from Ref. [119]. (a) the sensitivity to the dark Higgs mixing angle $\sin\alpha$ at CEPC (10^{10} Z) and at a Tera Z option (10^{12} Z) in a Higgs portal dark matter model, using the process $Z \to \ell^+\ell^-\tilde{s} \to \ell^+\ell^-(\bar{\chi}\chi)$. The model points on the gray dashed contour have correct thermal relic abundance under a specific assumption about the masses of the dark matter and the dark Higgs, as indicated by the arrow in the figure. (b) the sensitivity to the coupling Λ_{aBB} for an axion-like particle (ALP) model as a function of the ALP mass m_a, where B is the hypercharge gauge field. The signal process is $Z \to \gamma a$, where a can decay to a pair of photons (3γ), be detected as one photon due to high boost (2γ), or be detected as missing energy due to its long lifetime ($\gamma\not{E}$).

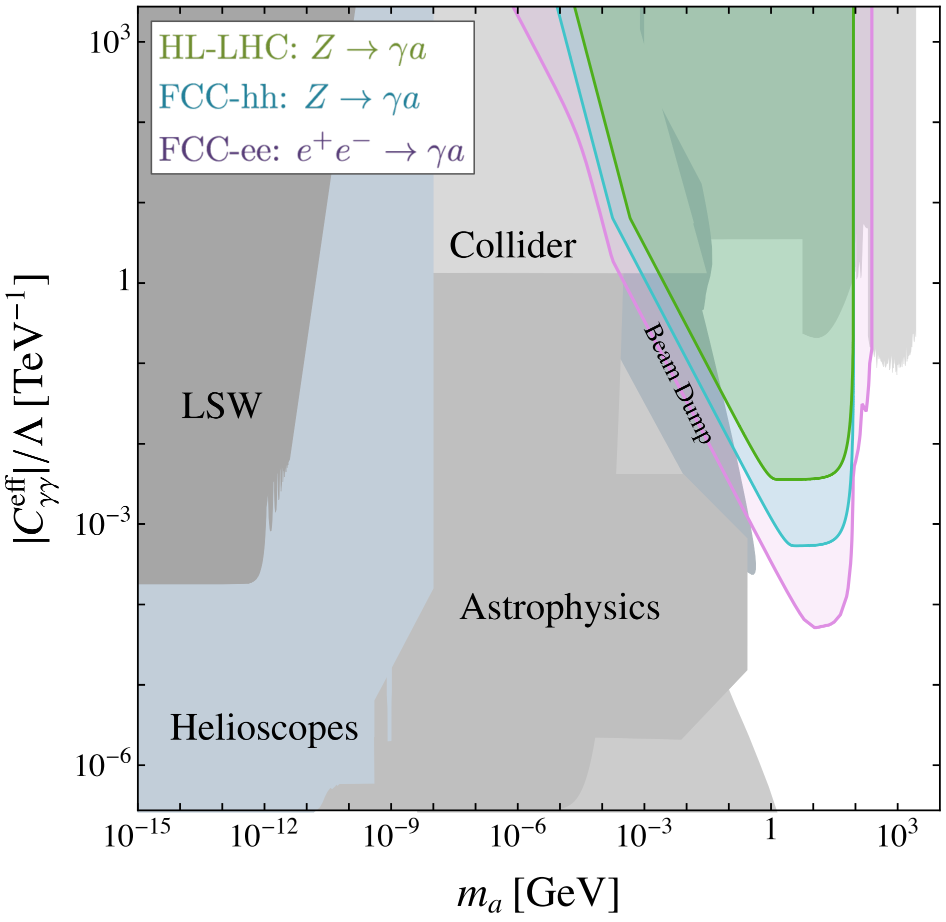
Axions and ALPs with photon coupling: CLIC



Source:
The CLIC potential for New Physics
arXiv: 1812.02093

Fig. 123: Projected exclusion contours for searches for $e^+e^- \to \gamma a \to 3\gamma$ (top left), $e^+e^- \to Za \to Z\gamma\gamma$ (top right) and $e^+e^- \to ha \to \bar{b}b\gamma\gamma$ (bottom left) for CLIC$_{380}$ (dark orange), CLIC$_{1500}$ (light orange), CLIC$_{3000}$ (yellow) assuming $c_2 = 0$. The constraints from other experiments are in grey in the background. For more details see [719,724].

Axions and ALPs with photon coupling: FCC-ee



Source: arXiv:1808.10323
Bauer, Neubert, Thamm.
Approved by FCC-ee contact person.

For FCC-ee this plot combines the L at the Z-pole, at sqrt(2 m_W) and at 240 GeV.

Axions and ALPs with photon coupling: FCC-hh

Source:1808.10323
Bauer, Neubert, Thamm.
Approved by the FCC-hh contact person.

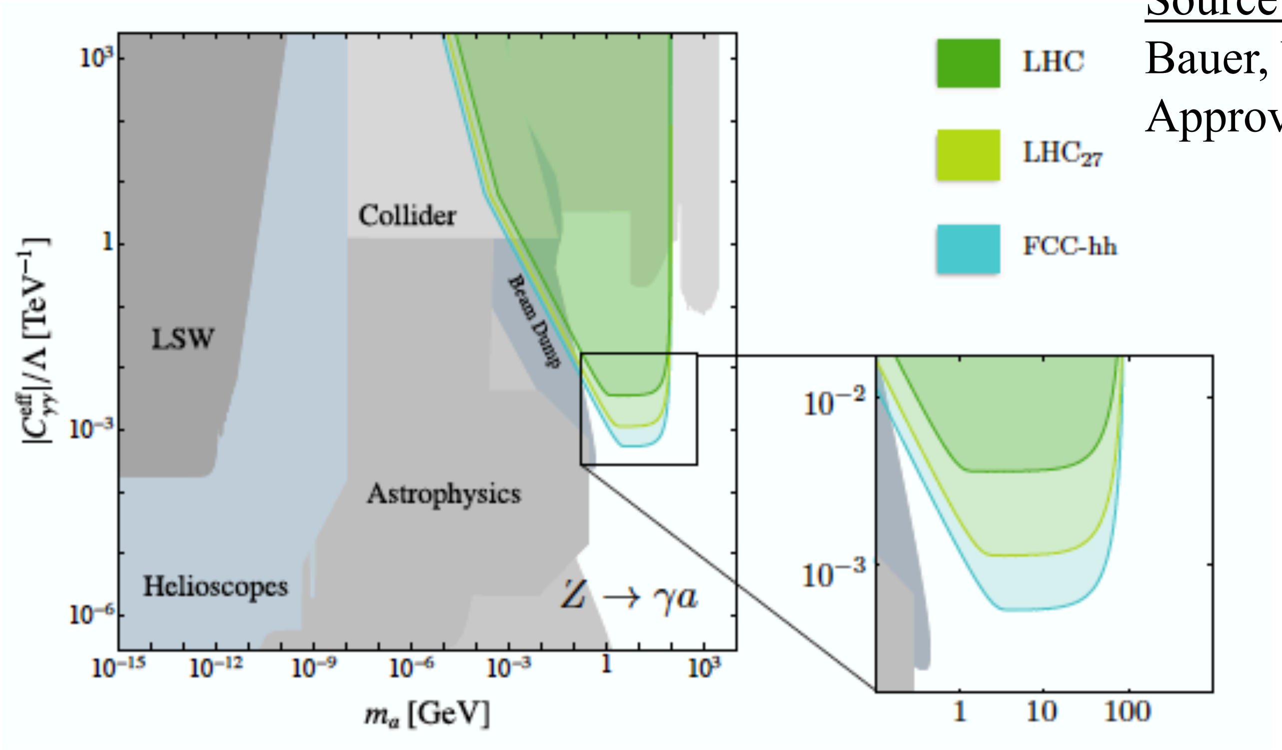


Figure 14: Parameter regions which can be probed in the decay $Z \to \gamma a$ with $a \to \gamma\gamma$ at hadron colliders . The projected reach is colored green (LHC), light green (HE-LHC) and turquoise (FCC-hh). We assume $\mathrm{Br}(a \to \gamma\gamma) = 1$.

Axions and ALPs with photon coupling: LHeC, FCC-eh, HE-LHeC

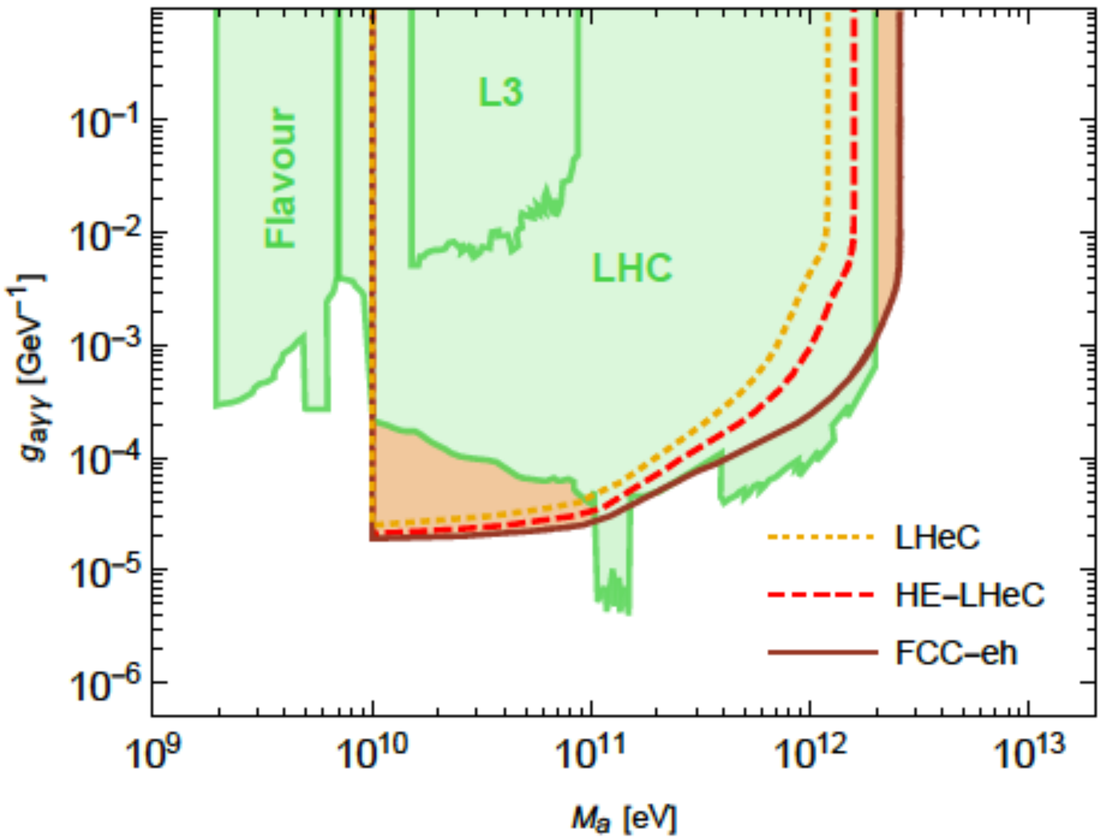


FIG. 3: Projected *ep* colliders sensitivity at 95% CL and existing constraints on the ALP with photon coupling. The green regions are experimentally excluded.

Source:
Chong-Xing Yue et al.
arXiv:1904.10657

Fermion portal
(sterile neutrinos)

$$y_N \, LHN$$

Relevant plots from official reports/papers

Fermion portal: **current limits + MATHUSLA, CODEX, FASER**

Source: CERN-PBC-REPORT-2018-007, arXiv: 1901.09966

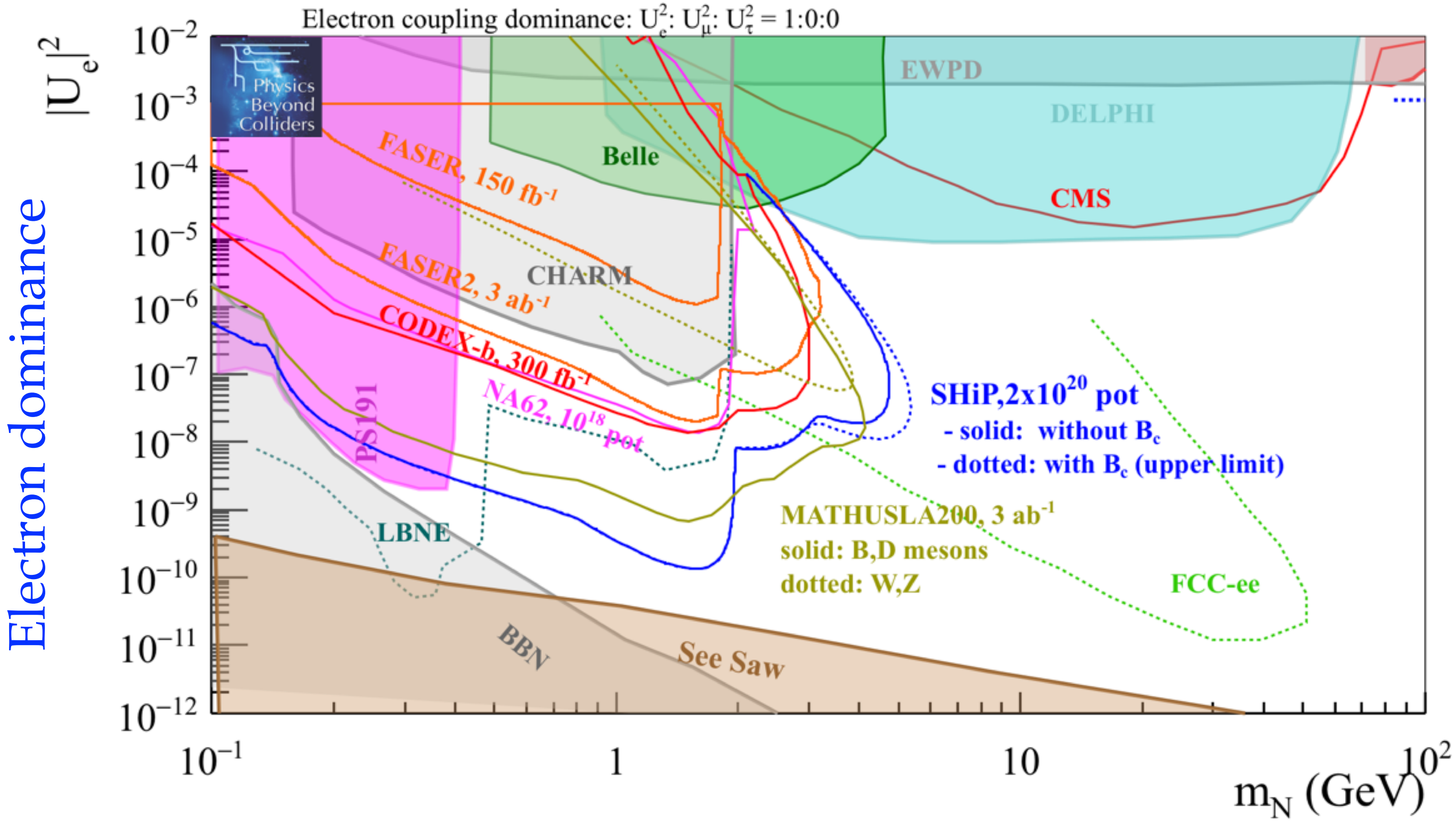
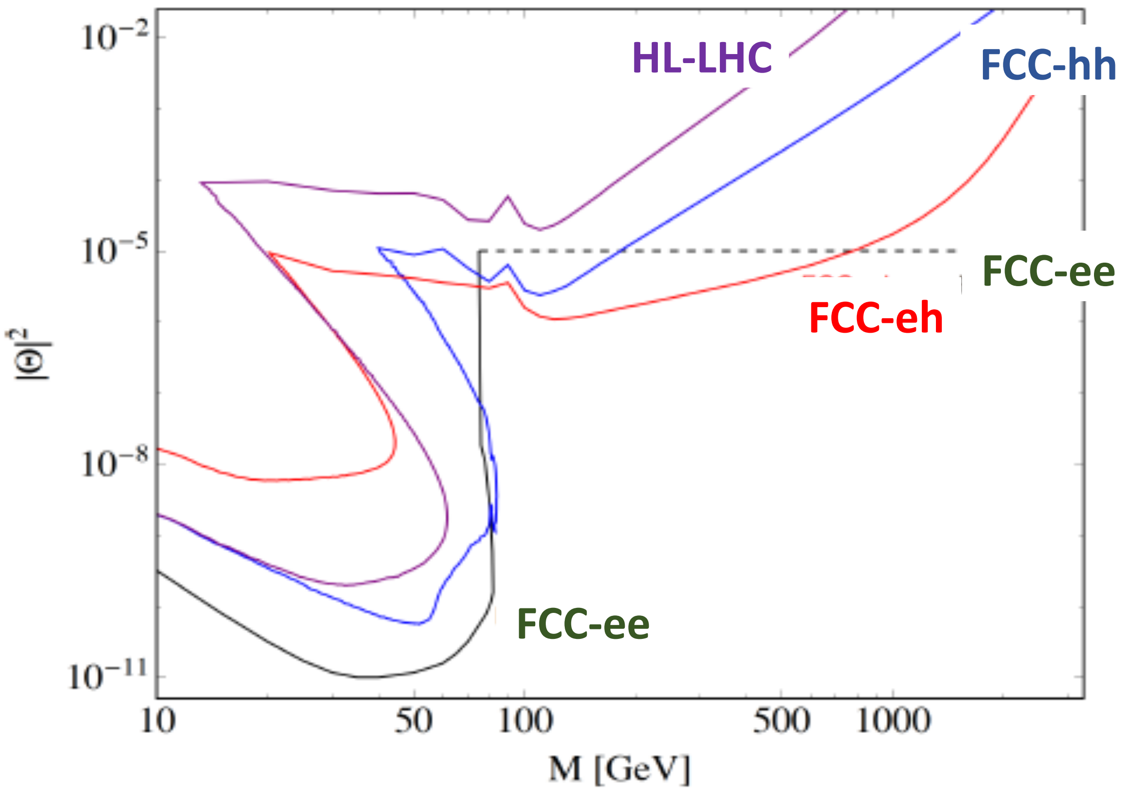


Figure 31: BC6: Sensitivity to Heavy Neutral Leptons with coupling to the first lepton generation only. Current bounds (filled areas) and 10-15 years prospects for PBC projects (SHiP, MATHUSLA200, CODEX-b and FASER2) (solid lines). Projections for a LBNE near detector with 5×10^{21} pot and from FCC-ee with 10^{12} Z^0 decays are also shown.

Fermion portal: FCC-ee, FCC-eh, FCC-hh



Source:
FCC report, Vol. 2
CERN-ACC-2018-0057

Figure 5: Left: FCC-hh mass reach for different s-channel resonances. Right: Summary of heavy sterile neutrino discovery prospects at all FCC facilities. Solid lines show direct searches at FCC-ee (black, in Z decays), FCC-hh (blue in W decays) and FCC-eh (in production from the incoming electron). The dashed line denotes the impact on precision measurements at the FCC-ee, it extends up to more than 60 TeV.

Fermion portal: **FCC-ee in more detail**

<u>Source</u>: FCC report, CERN-ACC-2018-0057 REV

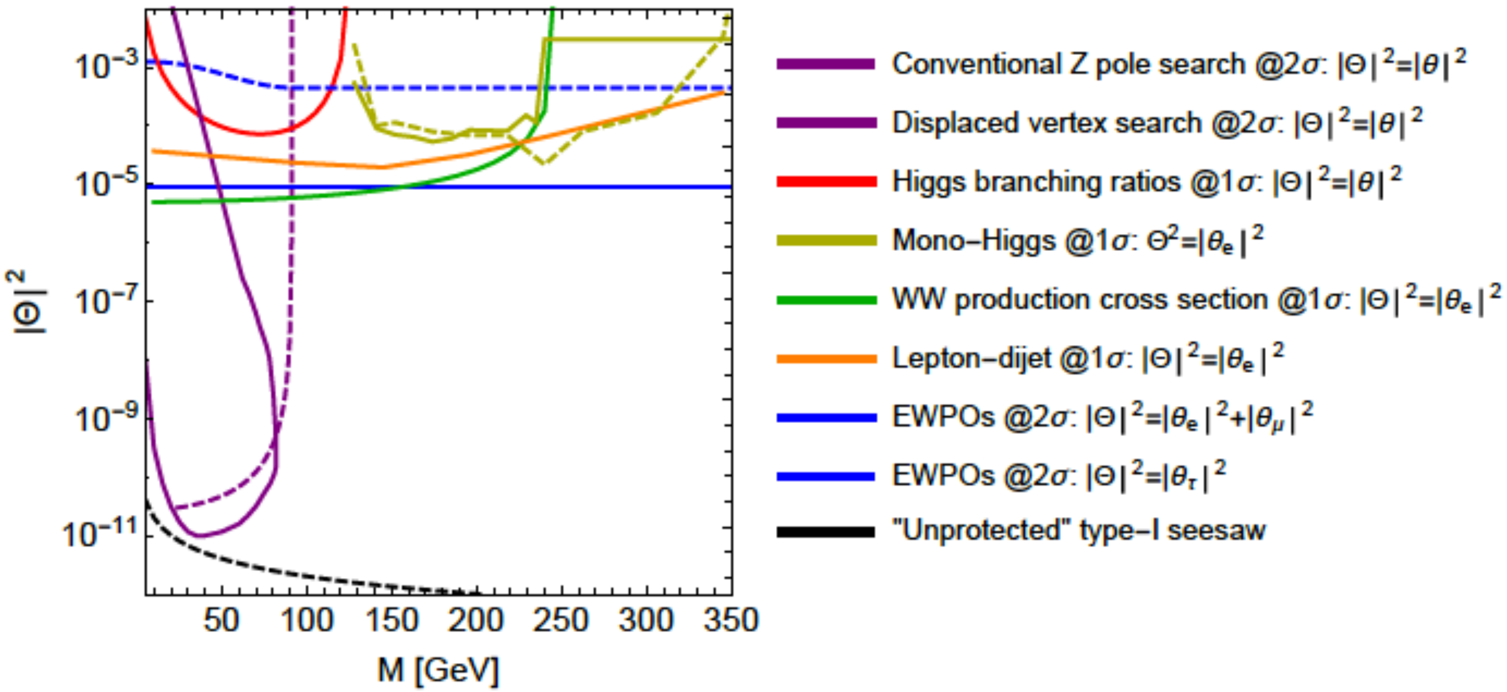
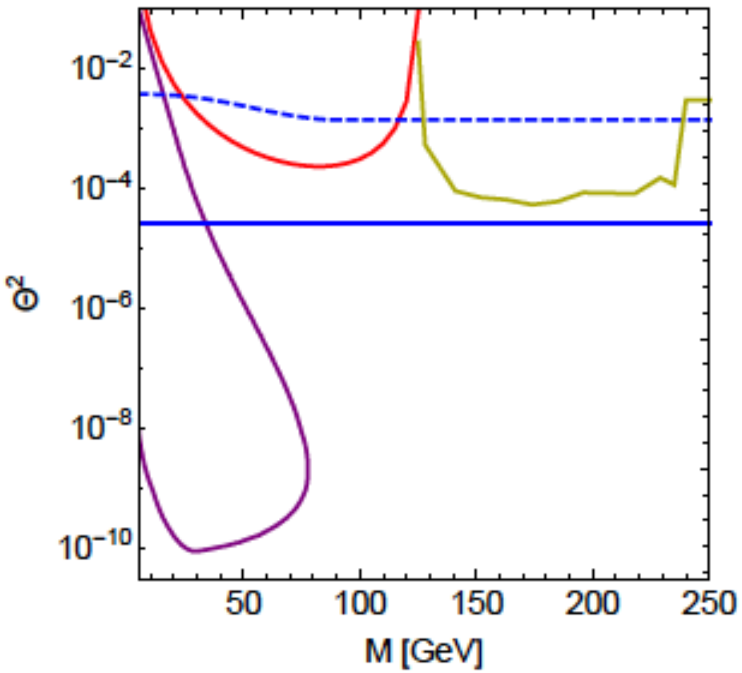


Figure 13.1: Sensitivities of the different signatures to the active-sterile mixing and masses of sterile neutrinos at the FCC-ee. For details on the signatures see Ref. [344].

Fermion portal: CEPC (1)



Source:
CEPC Physics case, arXiv:1811.10545

Figure 2.33: The CEPC's ability to probe heavy sterile neutrinos is expressed as a projected sensitivity on the active-sterile mixing angle, Θ, and the sterile neutrino mass scale, M. The blue (solid and dashed) line denotes electroweak precision measurements [292, 297, 311, 312]. The purple line denotes displaced vertex searches [313] at the Z-pole run with an integrated luminosity of 10 ab^{-1}. The yellow and red lines stem from the measurements of Higgs boson production [295, 296] and decay [297] for an integrated luminosity of 5 ab^{-1} at $\sqrt{s} = 240$ GeV.

Fermion portal: CEPC (2)

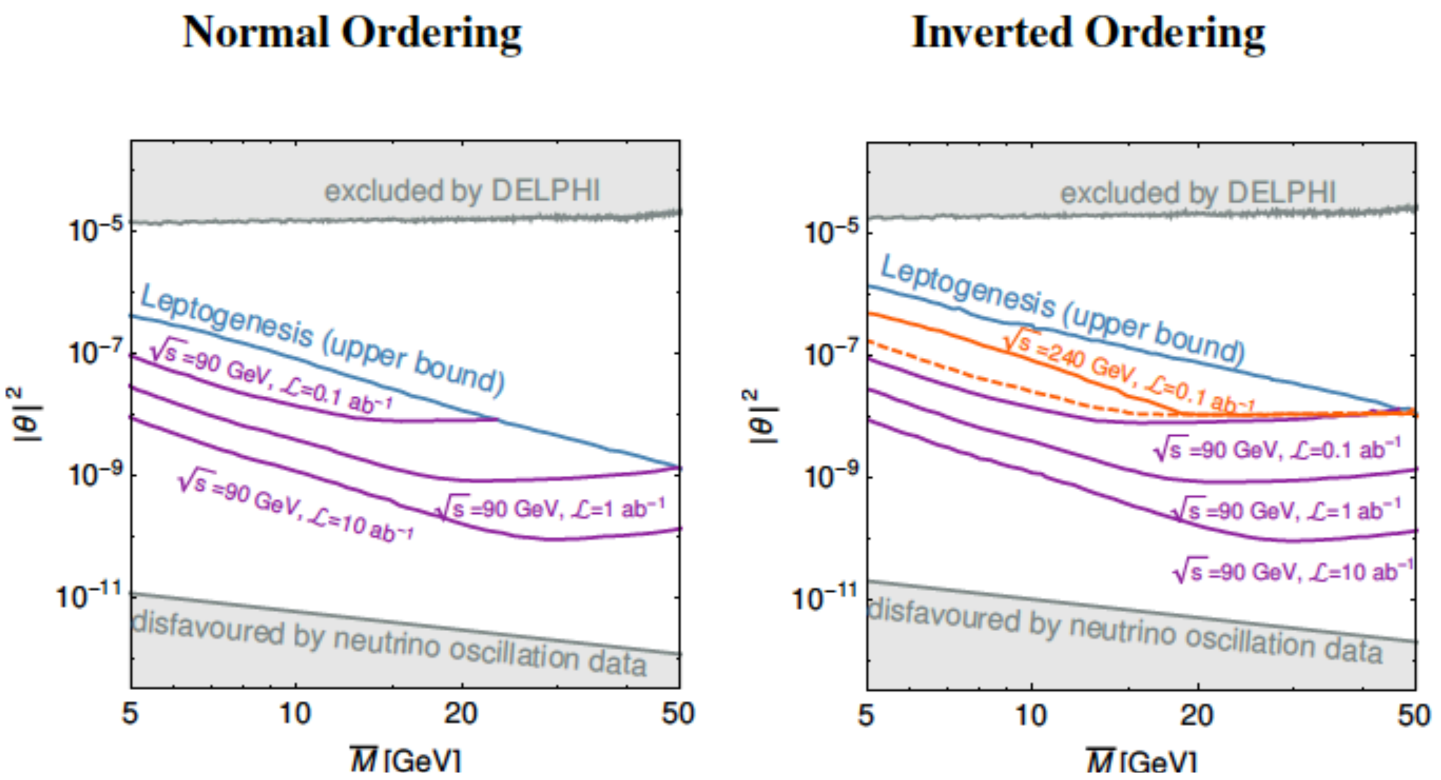
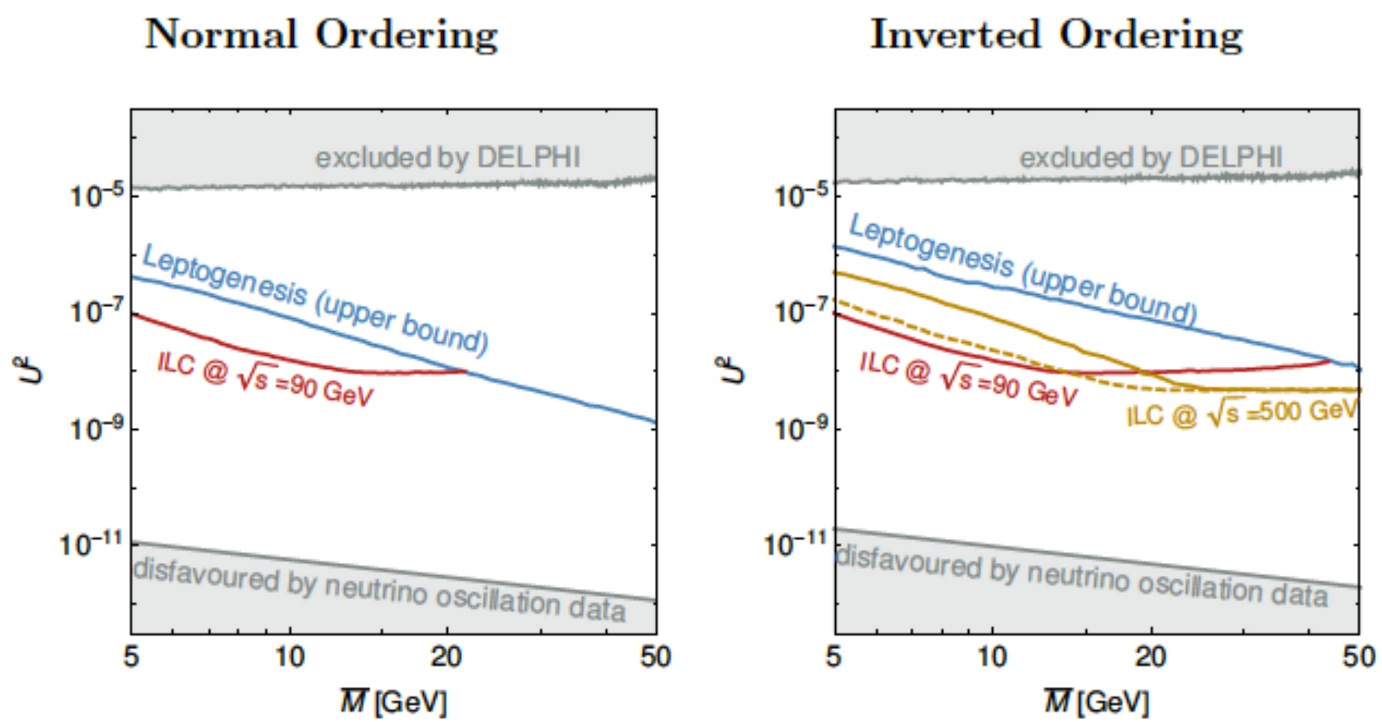


Figure 2.34: CEPC's capacity to test models of leptogenesis. The parameter space for a minimal Type I Seesaw model with $n_s = 2$ is shown; the two sterile neutrino masses, M_1 and M_2, are combined to form $\bar{M} = (M_1 + M_2)/2$ (with $|M_2 - M_1|/(M_2 + M_1) < 0.1$), and θ represents the active-sterile mixing angle. Models in the parameter space below the blue line are consistent with the observed baryon asymmetry of the universe through leptogenesis. Models above the orange lines are tested by CEPC at $\sqrt{s} = 240$ GeV, which is expected to observe at least four displaced vertex events. Models above the purple lines are probed by CEPC at the Z pole. The gray areas are ruled out by the DELPHI experiment [328, 329] (top) and current neutrino oscillation data (bottom). The figure is based on Ref. [261]. Note that for $n_s = 3$ heavy neutrinos, the "leptogenesis" upper bound is expected to be much higher [330] and practically identical to the DELPHI constraint, so that CEPC at 240 GeV can enter the cosmologically interesting parameter region for both hierarchies.

Source: CEPC physics case:
arXiv: 1811.10545

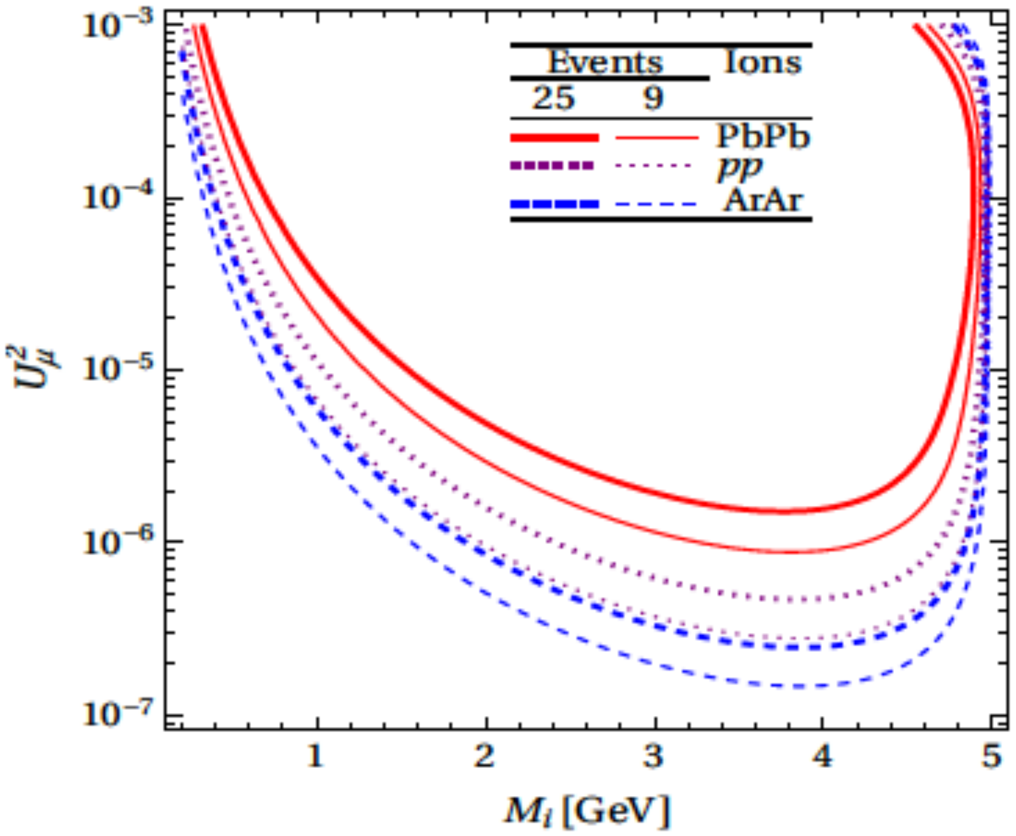
Fermion portal: ILC



Source: Antush et al. 1710.03744.

Figure 5: *The blue "BAU" line shows the largest possible U^2 for which the BAU can be generated for given $\bar{M}$, as found in the parameter scan described in section 3.3. The other coloured lines mark the parameter regions in which future lepton colliders can observe at least four expected displaced vertex events from N_1 with properties that are consistent with successful leptogenesis. The solid and dashed lines correspond to the "guaranteed discovery area" and "potential discovery area" discussed in section 3.3. The grey area is disfavoured by DELPHI (on the top) and the neutrino oscillation data (at the bottom). We show no lower bound on U^2 from leptogenesis because it is lower than the constraint from neutrino oscillation data in this mass range. More details are given in the main text, cf. section 5.1.*

Fermion portal: LHC Heavy Ions prospects

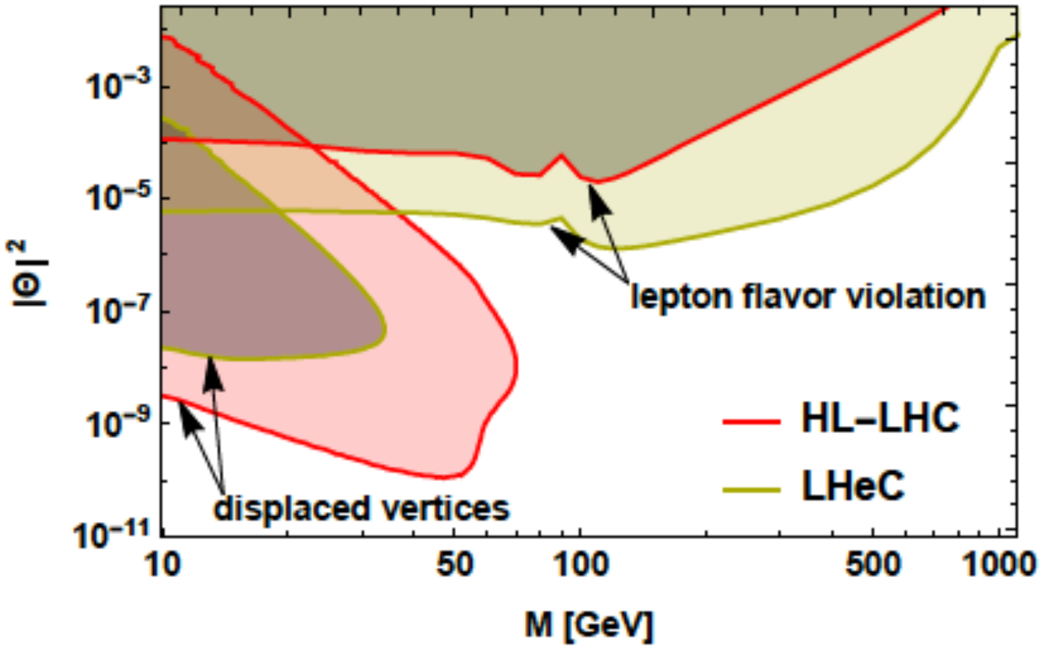


Source: ESPP input #151
New Physics in Heavy Ions collisions
referring to the paper:
Drewes et al, 1810.04400

π

Figure 2: Left: Lower bounds for the magnetic monopole mass vs. units of magnetic charge [70]. Right: Estimated CMS reach for heavy neutrinos, with mass M_i and muon-neutrino mixing angle U_μ, from B-meson decays in pp, ArAr, and PbPb collisions with equal running time [71].

Fermion portal: LHeC



Source: #159 submitted to ESPP
"Exploring the Energy Frontier with Deep Inelastic Scattering at the LHC," plot based on arXiv:1612.02728

Figure 4: Left: Prospects for direct right-handed neutrino searches at the LHeC, first estimates for HL-LHC prospects for comparison, based on [34].

Fermion portal: HL-LHC, HE-LHC, FCC-hh

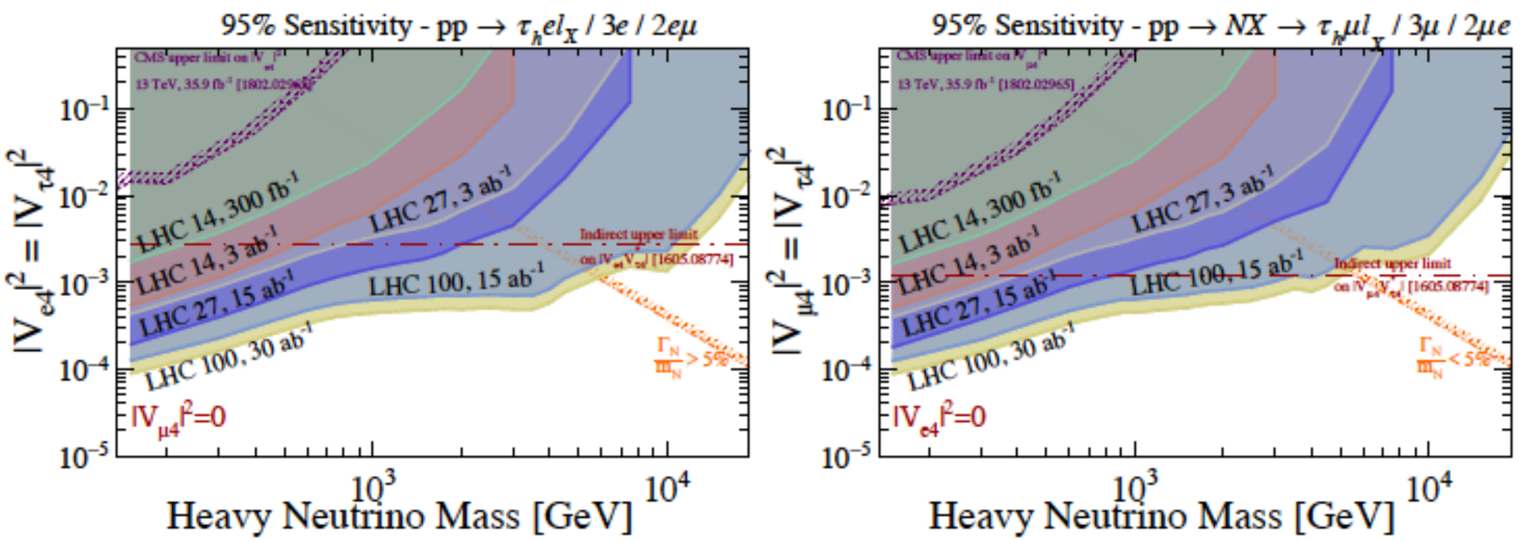


Fig. 5.1.2: Top: sensitivity to the active-heavy mixing $|V_{\ell N}|^2$ as a function of the heavy neutrino mass m_N in the trilepton final states (left) $\tau_h^{\pm} e^{\mp} \ell_X$ +MET and (right) $\tau_h^{+} \tau_h^{-} \ell_X$ +MET, assuming $|V_{e4}|^2 = |V_{\tau4}|^2$ and $|V_{\mu4}|^2 = 0$, at the $\sqrt{s}$ = 14 TeV LHC. The dash-diamond line corresponds to the standard analysis with a b-jet veto while the solid-star line is the jet veto-based analysis [372, 373]. Bottom: for the benchmark mixing hypotheses (left) $|V_{e4}| = |V_{\tau4}|$ with $|V_{\mu4}| = 0$ and (right) $|V_{\mu4}| = |V_{\tau4}|$ with $|V_{e4}| = 0$, the projected sensitivity at $\sqrt{s}$ = 27 TeV and 100 TeV using the trilepton analysis of Ref. [372].

Source:
Beyond the Standard Model Physics at the HL-LHC and HE-LHC, arXiv:1812.07831