BSM physics at the LHeC and the FCC-eh

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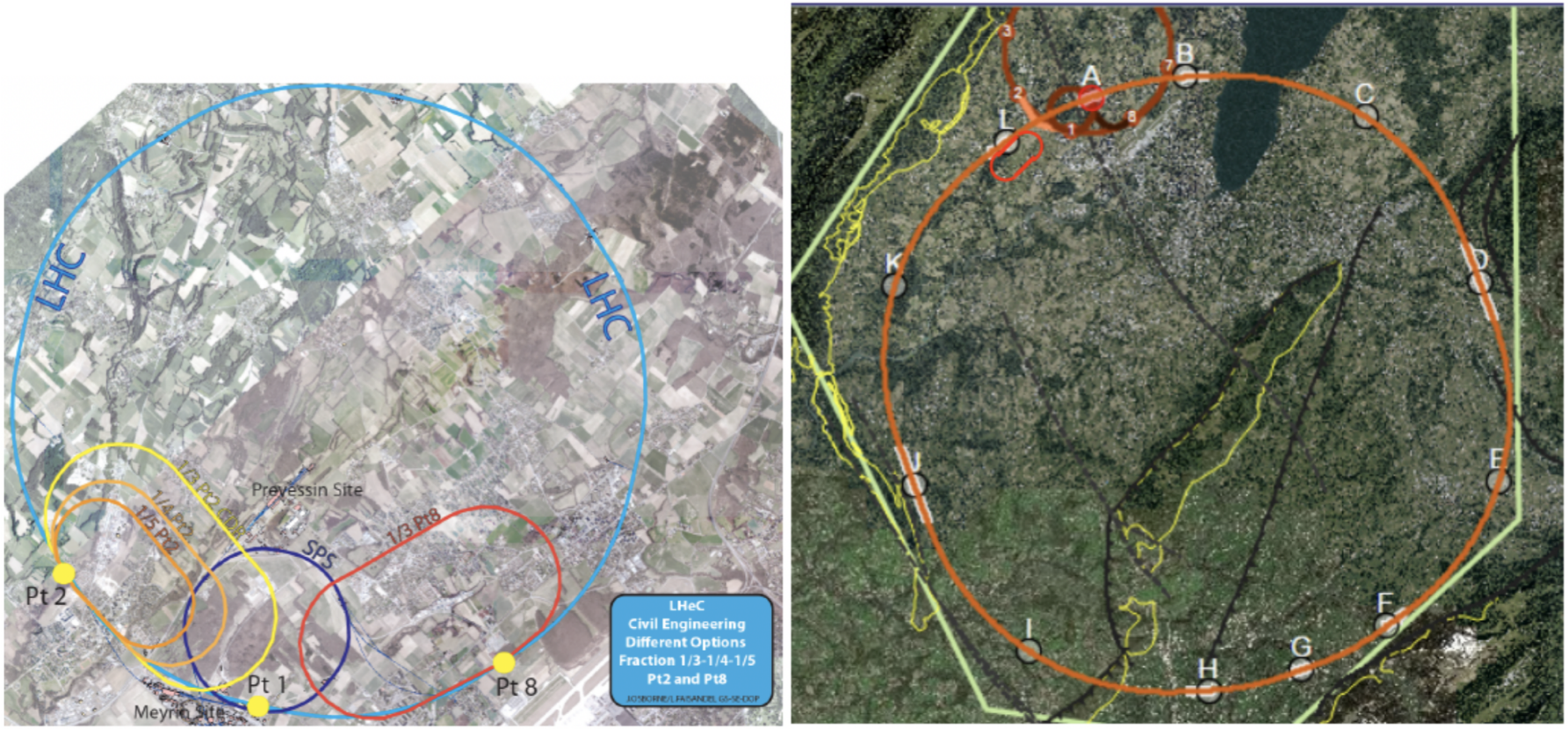
on behalf of the BSM@ep group
Convenors: G. Azuelos, O. Fischer, M. D'Onofrio

EPS conference
Ghent, 12.07.19

Possible Layouts for the LHeC and FCC-he



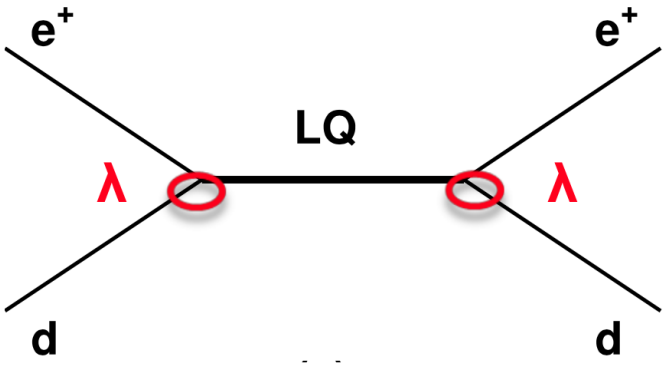
- Energy Recovering Linac (e beam: 60 GeV).
- Operation of LHeC (FCC-he) concurrent with LHC (FCChh).
- ERL can be compatible with FCC ring design.

Motivation for Beyond the Standard Model studies

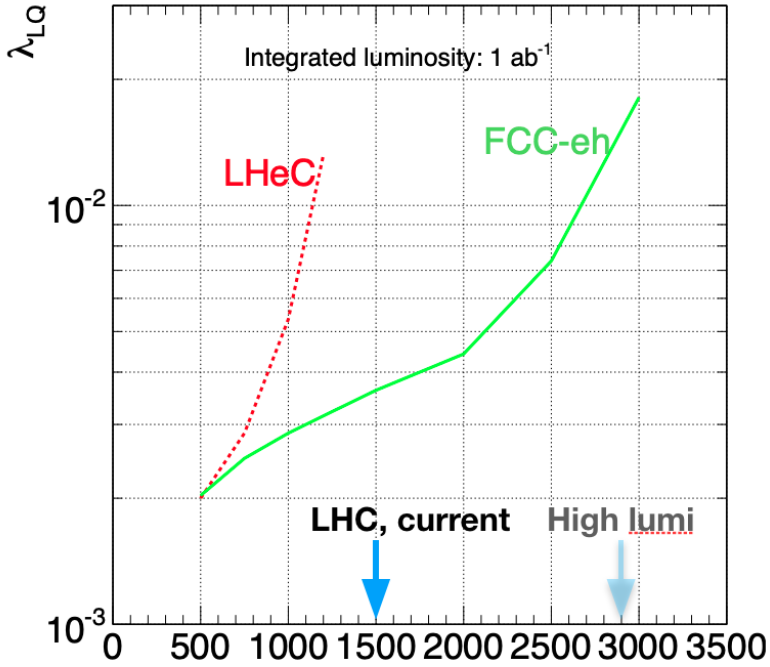
Collider	Type	$\sqrt{s}$	$\mathscr{P}$ [%] $[e^-/e^+]$	N(Det.)	$\mathscr{L}_{\text{inst}}$ $[10^{34}]\,\text{cm}^{-2}\text{s}^{-1}$	$\mathscr{L}$ $[\text{ab}^{-1}]$	Time [years]	Refs.	Abbreviation
HL-LHC	pp	14 TeV	-	2	5	6.0	12	[10]	HL-LHC
HE-LHC	pp	27 TeV	-	2	16	15.0	20	[10]	HE-LHC
FCC-hh	pp	100 TeV	-	2	30	30.0	25	[1]	FCC-hh
FCC-ee	ee	M_Z	0/0	2	100/200	150	4	[1]	
		$2M_W$	0/0	2	25	10	1-2		
		240 GeV	0/0	2	7	5	3		FCC-ee$_{240}$
		$2m_{top}$	0/0	2	0.8/1.4	1.5	5		FCC-ee$_{365}$
							(+1)	(1y SD before $2m_{top}$ run)	
ILC	ee	250 GeV	±80/±30	1	1.35/2.7	2.0	11.5	[3,11]	ILC$_{250}$
		350 GeV	±80/±30	1	1.6	0.2	1		ILC$_{350}$
		500 GeV	±80/±30	1	1.8/3.6	4.0	8.5		ILC$_{500}$
							(+1)	(1y SD after 250 GeV run)	
CEPC	ee	M_Z	0/0	2	17/32	16	2	[2]	CEPC
		$2M_W$	0/0	2	10	2.6	1		
		240 GeV	0/0	2	3	5.6	7		
CLIC	ee	380 GeV	±80/0	1	1.5	1.0	8	[12]	CLIC$_{380}$
		1.5 TeV	±80/0	1	3.7	2.5	7		CLIC$_{1500}$
		3.0 TeV	±80/0	1	6.0	5.0	8		CLIC$_{3000}$
							(+4)	(2y SDs between energy stages)	
LHeC	ep	1.3 TeV	-	1	0.8	1.0	15	[9]	LHeC
HE-LHeC	ep	2.6 TeV	-	1	1.5	2.0	20	[1]	HE-LHeC
FCC-eh	ep	3.5 TeV	-	1	1.5	2.0	25	[1]	FCC-eh

- **Electron-proton collider:** ideal laboratory to study common features of electrons and quarks with EW / VBF production, LQ,multi-jet final states, forward objects
- **Promising aspects:**
  - Small background (no QCD interaction between e and p)
  - Very low pileup
- Here I give a short overview over a few selected topics.

Leptoquark searches in electron-proton collisions



work by G. Azuelos



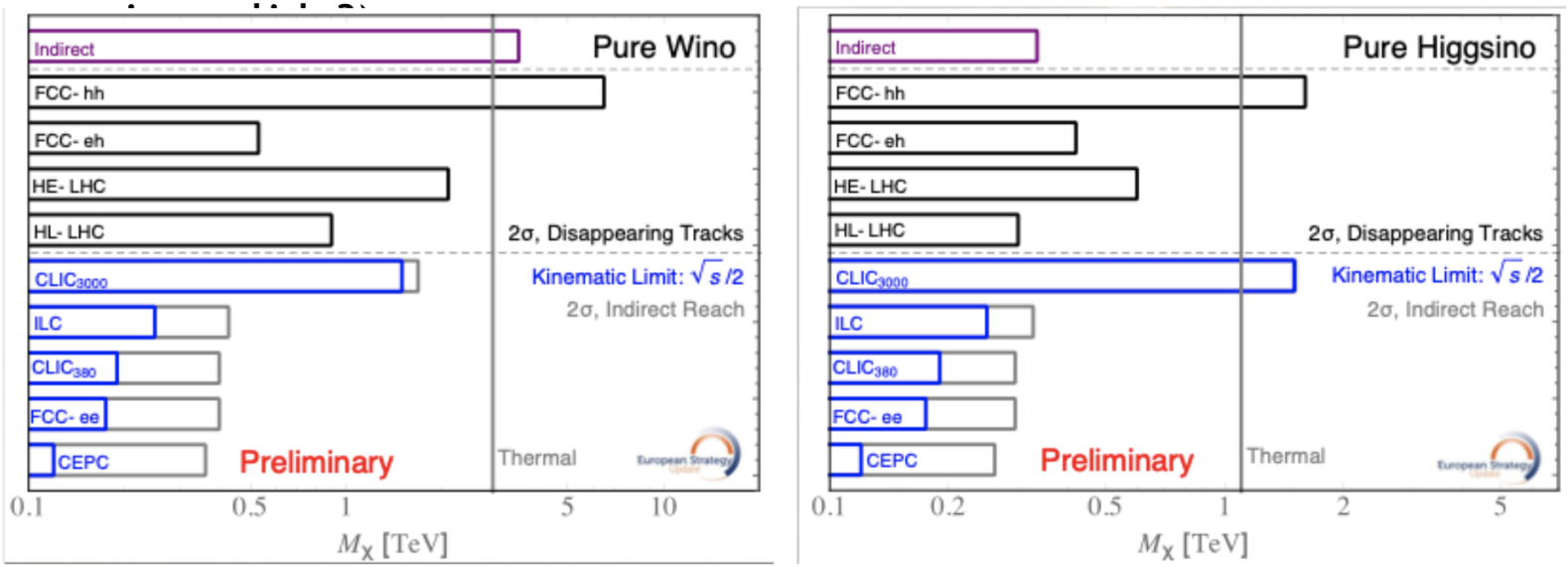
- Recent motivation from LHCb anomalies (theory explanations typically involve 3^{rd} generation).
- Phenomenology equivalent to R-parity violating SUSY.
- ATLAS limits 1.5 TeV for 1,2 generations [1902.00377]
- CMS limits 1 TeV [1901.03570]
- In ep collisions singly produced as *s* channel resonance.

$\Rightarrow$ Very sensitive to 1^{st} generation.

$\Rightarrow$ Can measure: Spin, quantum numbers, flavor structure.

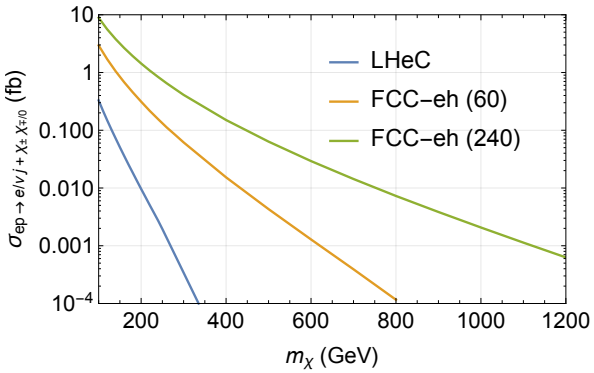
cf. also: Zhang, Yue, Liu; Mod. Phys. Lett. A **33** (2018) no.06, 1850039

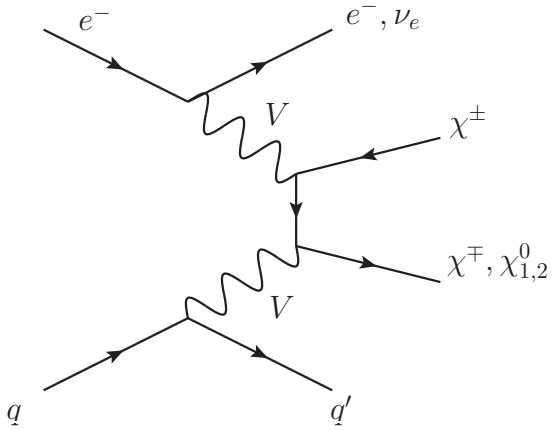
Wino and Higgsino Dark Matter

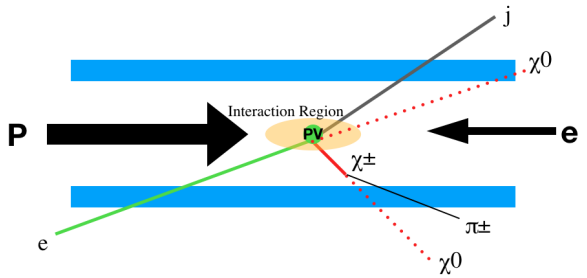


- WIMPs are still a viable solution for Thermal DM (e.g. in many SUSY extensions/regions)
- Being broadly probed by Direct and Indirect detection as well as Colliders
- At e-p colliders, wino and higgsino DM can be searched for using disappearing track analyses

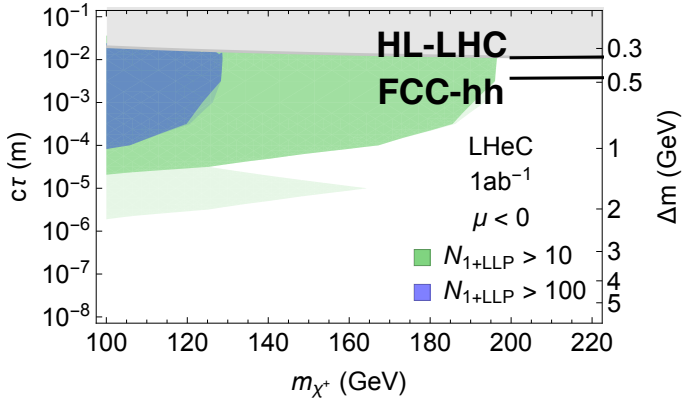
Long-lived Higgsino searches

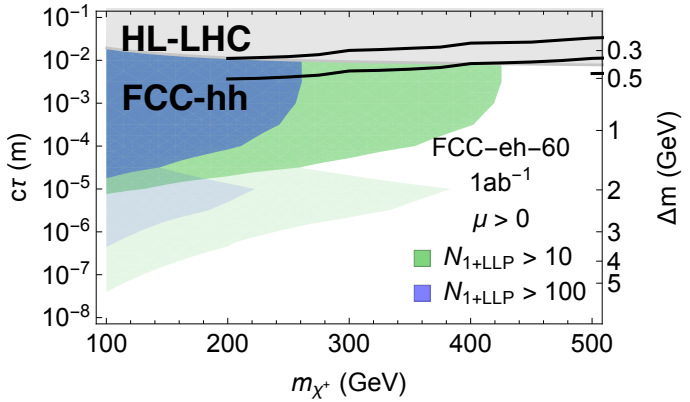






- Production via vector boson fusion
- Charginos can have very short lifetime $c\tau \sim \mu$m.
- Decay products $P_T = \mathcal{O}(100)$ MeV
- Beam remnant jet $\Rightarrow$ primary vertex with $\mathcal{O}(10)\,\mu$m precision
- Signal: single soft displaced pion.
- Looks like hadronic noise, but can be detected at ep colliders!





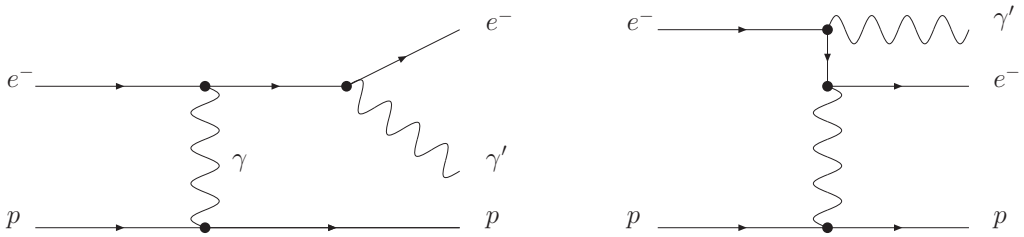
Curtin, Deshpande, Fischer, Zurita; [arXiv:1712.07135]

Dark Sectors

- Portal models to test generic dark sectors as benchmarks as discussed at the ESPP.
- New results from e-p presented in Granada and being documented.
- Vector portal: $-\frac{\epsilon}{2\cos\theta_W} F'_{\mu\nu} B^{\mu\nu}$
  - Vector mediator (dark photon) for light thermal Dark Matter
  - New mass scale in the MeV-GeV range, feebly-coupled to SM
- Scalar portals: $(\mu S + \lambda S^2) H^\dagger H$
  - Higgs decays into a pair of long-lived fermionic particles X.
  - Recastable into renormalizable models.
- Pseudo-scalar portals: $\frac{a}{f_a} \tilde{F}_{\mu\nu} F^{\mu\nu}$
  - Search for axions/ALPs in the MeV-tens of GeV range.
  - Signature (e.g. diphoton) can allow determination of its mass.

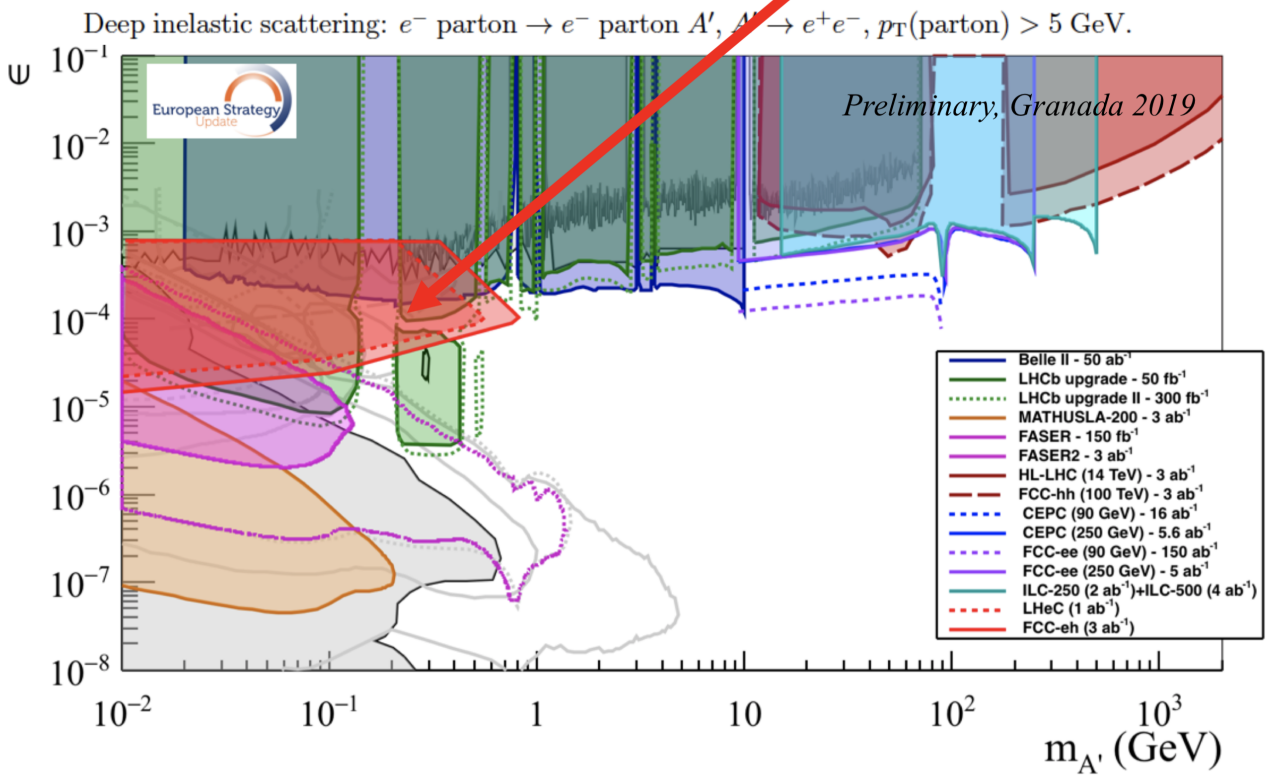
Dark Photons at the LHeC and the FCC-he

from G. Lanfranchi, Granada



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

Mixing between dark photon and SM photon

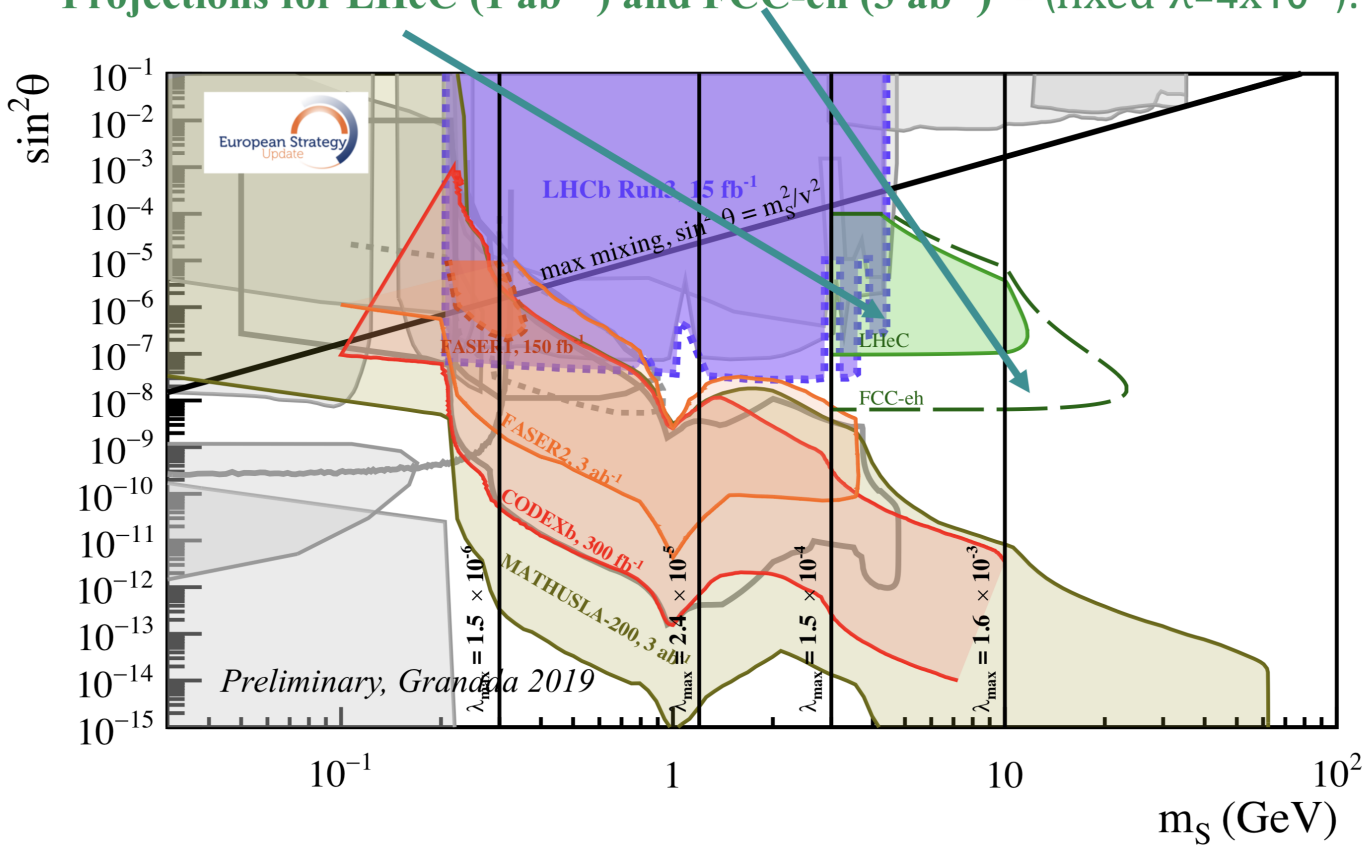


Electron-proton colliders can close a mass gap around 1 GeV via searches for displaced decays.

Scalar portal at the LHeC and the FCC-he

from G. Lanfranchi, Granada

Mixing between scalar and SM Higgs

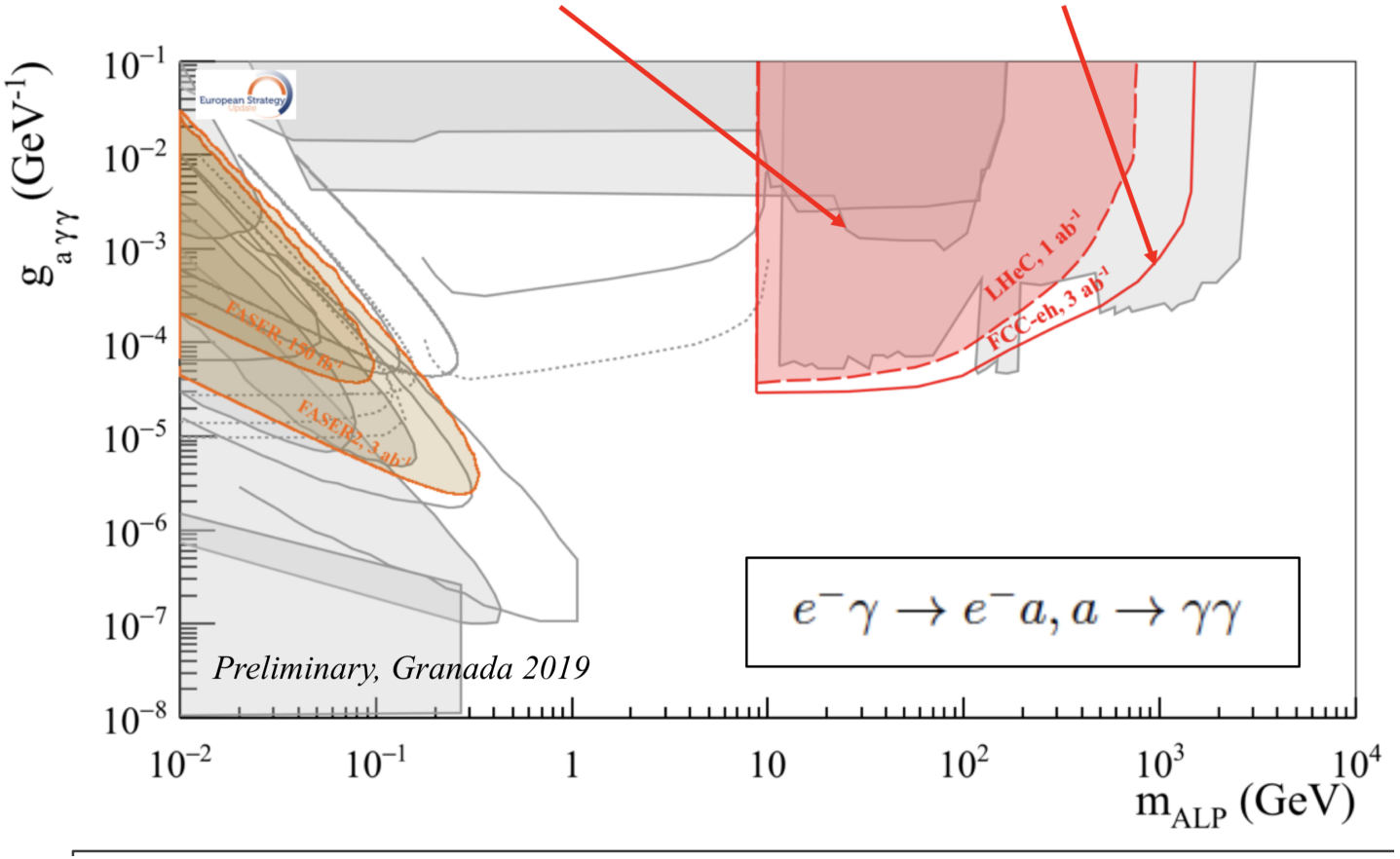


Recast from exotic Higgs decays into LLPs from: Curtin, Deshpande, Fischer, Zurita; [arXiv:1712.07135]

- Higgs decays into a pair of long-lived scalar particles S.
- Scalars decay into the heaviest SM fermion: $S \to f\bar{f}$.
- Assumption: $P_T(f) > 400$ MeV, displacement $> 50\,\mu$m with 100% detection efficiency

Pseudoscalar portal at the LHeC and the FCC-he

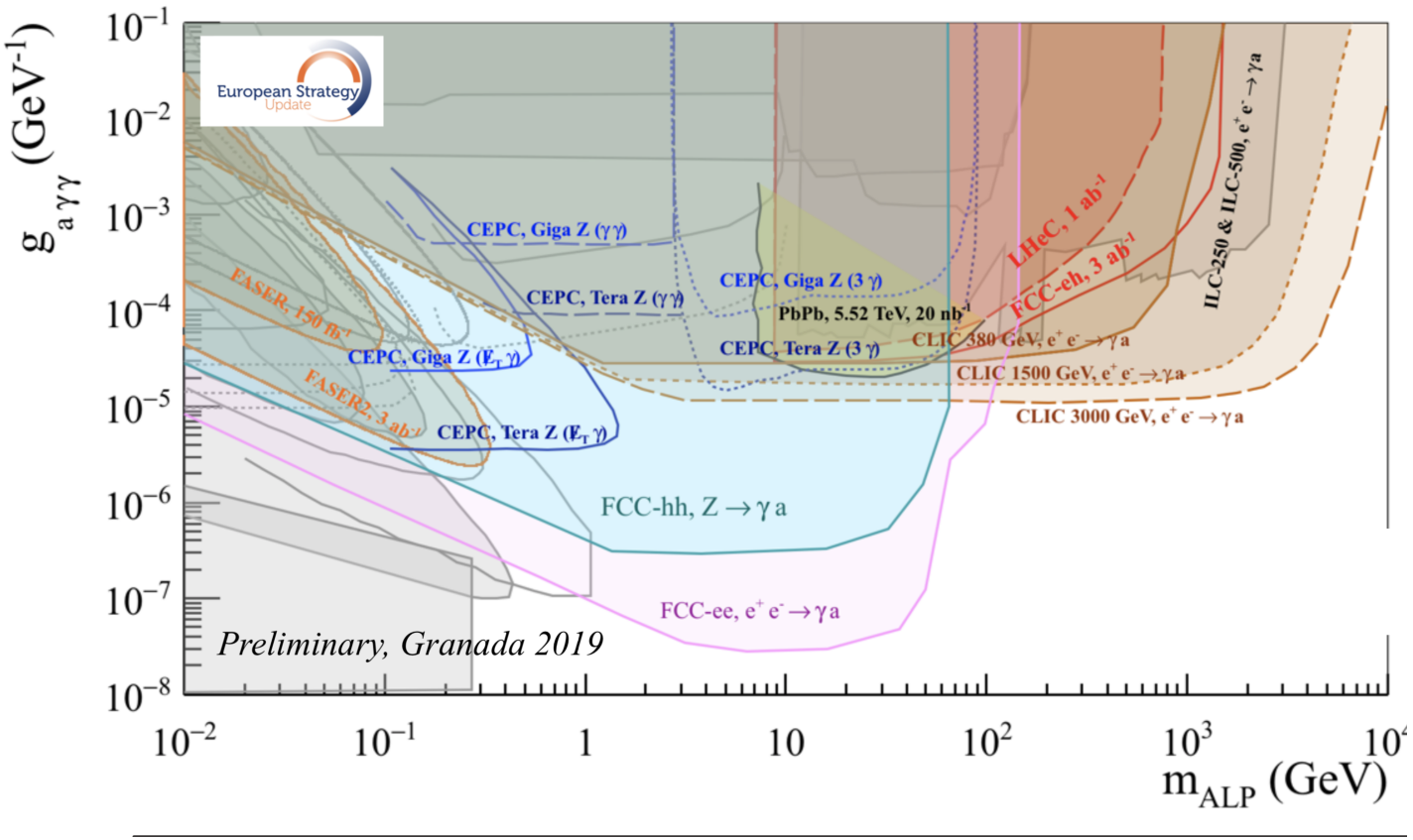
Prospects for LHeC with 1/ab and FCC-he with 3/ab



- Alp production from electron-photon scattering.
- Signature: diphoton with invariant mass $\sim m_{\mathrm{Alp}}$.
- Gray: present exclusion limits.

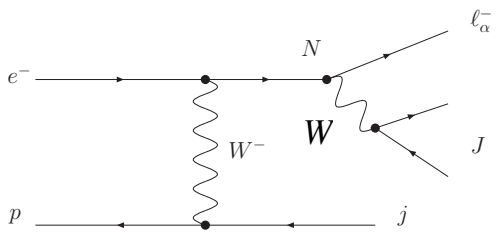
Pseudoscalar portal at the LHeC and the FCC-he

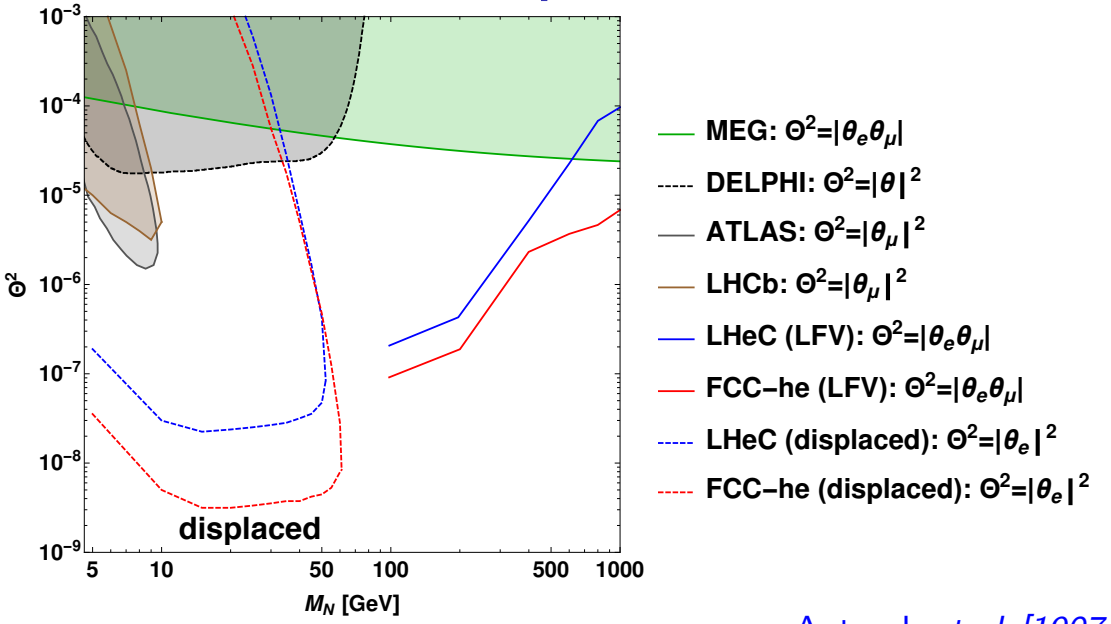
Prospects for LHeC with 1/ab and FCC-he with 3/ab



- Alp production from electron-photon scattering.
- Signature: diphoton with invariant mass $\sim m_{\mathrm{Alp}}$.
- Gray: present exclusion limits.

Sterile neutrinos at future electron-proton colliders





Antusch *et al. [1907.ASAP]*

- Lowscale seesaw models allow large production xsections at colliders.
- Paramters: mass M_N and the active-sterile mixing angles θ_α
- Present constraints: $|\theta_e| \leq 10^{-5}$,
- Comprehensive comparison between collider types in

Antusch *et al.* Int. J. Mod. Phys. A **32** (2017) no.14, 1750078

- Promising at ep:
  - lepton-flavor violating final states: μ +jets, τ + jets
  - displaced vertices for $M_N < m_W$.

Many other studies

- Light Sleptons and EWkinos — K. Wang, S. Iwamoto, M. D'Onofrio, G. Azuelos
- Prompt EWkinos — Han, Li, Pan, Wang, [arXiv:1802.03679]
- Charged scalar bosons — Azuelos, Sun, Wang; [arXiv:1712.07505]
- Effective Majorana Neutrino Interactions and Polarization — Duarte, Zapata, Sampayo; [arXiv:1802.07620]
- Georgi-Machacheck model — Azuelos, Sun, Wang; [arXiv:1712.07505]
- Extended Higgs sectors — Liu, Tang, Zhang, Zhu; [arXiV:1608.08458]; Sun, Luo, Wei, Liu; [arXiv:1710.06284]; Hernández-Sánchez, Flores-Sánchez, Honorato, Moretti, Rosado; [arXiv:1612.06316]
- Leptoquarks and Heavy Neutrinos at the LHeC — S. Mandal, M. Mitra and N. Sinha; Phys. Rev. D **98** (2018) no.9, 095004
- RPV SUSY.
- Exotic/rare top decays.
- ...

Conclusions

- ep collider are complementary to pp and ee colliders. (Essential to fully exploit pp measurements due to PDF.)
- They offer a variety of opportunities for BSM searches.
- Ideal to study properties of new particles with couplings to electron-quark
- New opportunities for displaced signatures from LLPs:
  - Great reach for short lifetimes
  - Well suited to find signal that looks like hadronic noise.