Long lived particles at future lepton colliders

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The 2021 International Workshop on the High Energy Circular Electron Positron Collider

NAWI Graz
Natural Sciences

FWF
Der Wissenschaftsfonds.

UNI GRAZ

Preparing for the future

- Many options for future lepton colliders (irrespective of the exact luminosity on plot)
- Two energy ranges, either ‘h/Z factories’ or ‘high energy’
- Lots of room for new physics exploration

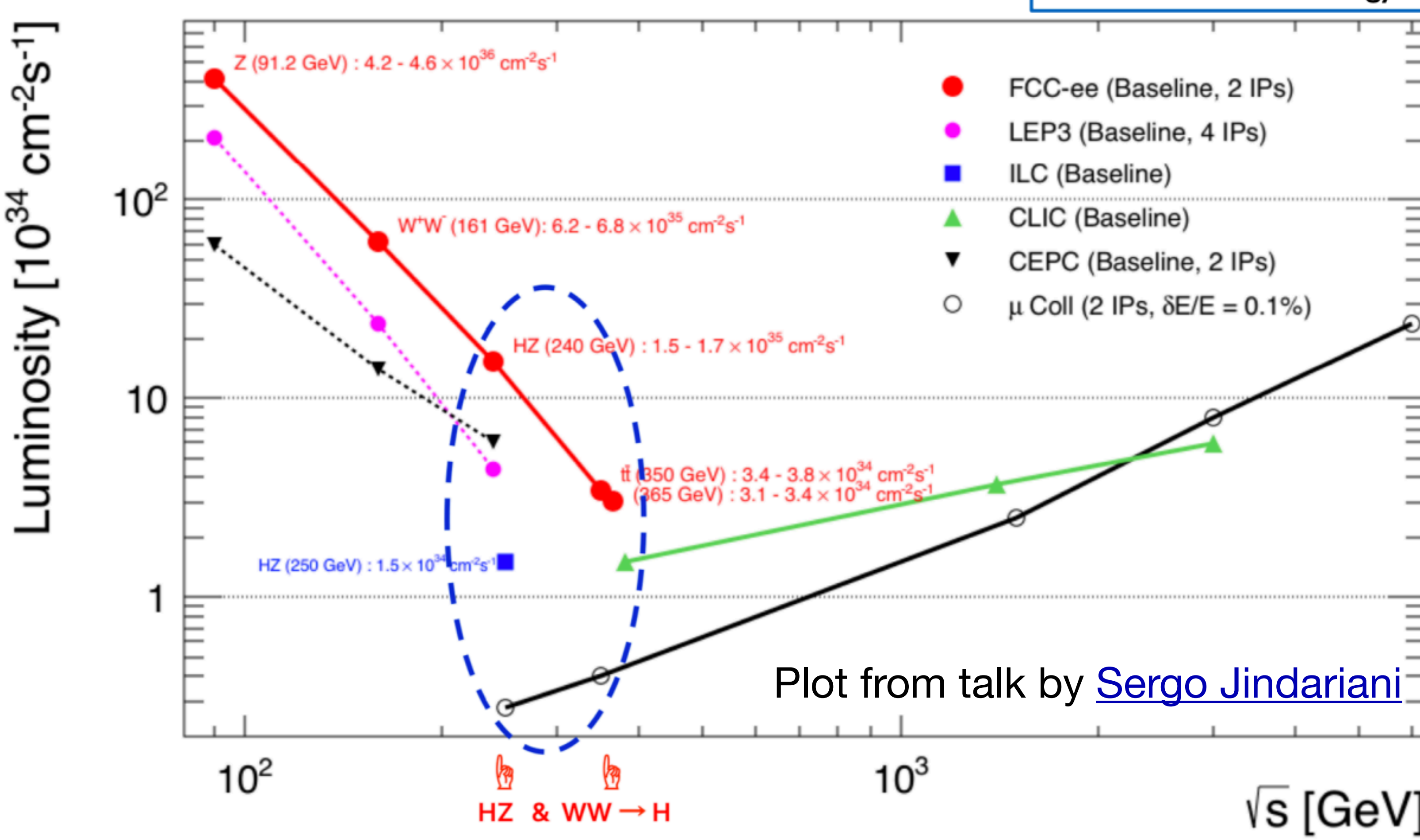
NB: lots of great opportunities for Belle-II physics program as well, however it isn’t ‘future’ collider anymore!

As the trajectory of a charged particle is deflected, it emits “synchrotron radiation”

$$\text{Radiated Power} \propto \frac{1}{\rho^2}\left(\frac{E}{m}\right)^4$$

Radius of curvature

An electron will radiate about 10^9 times more power than a muon of the same energy



30 TeV ?

Note logarithmic scale

Preparing for the future

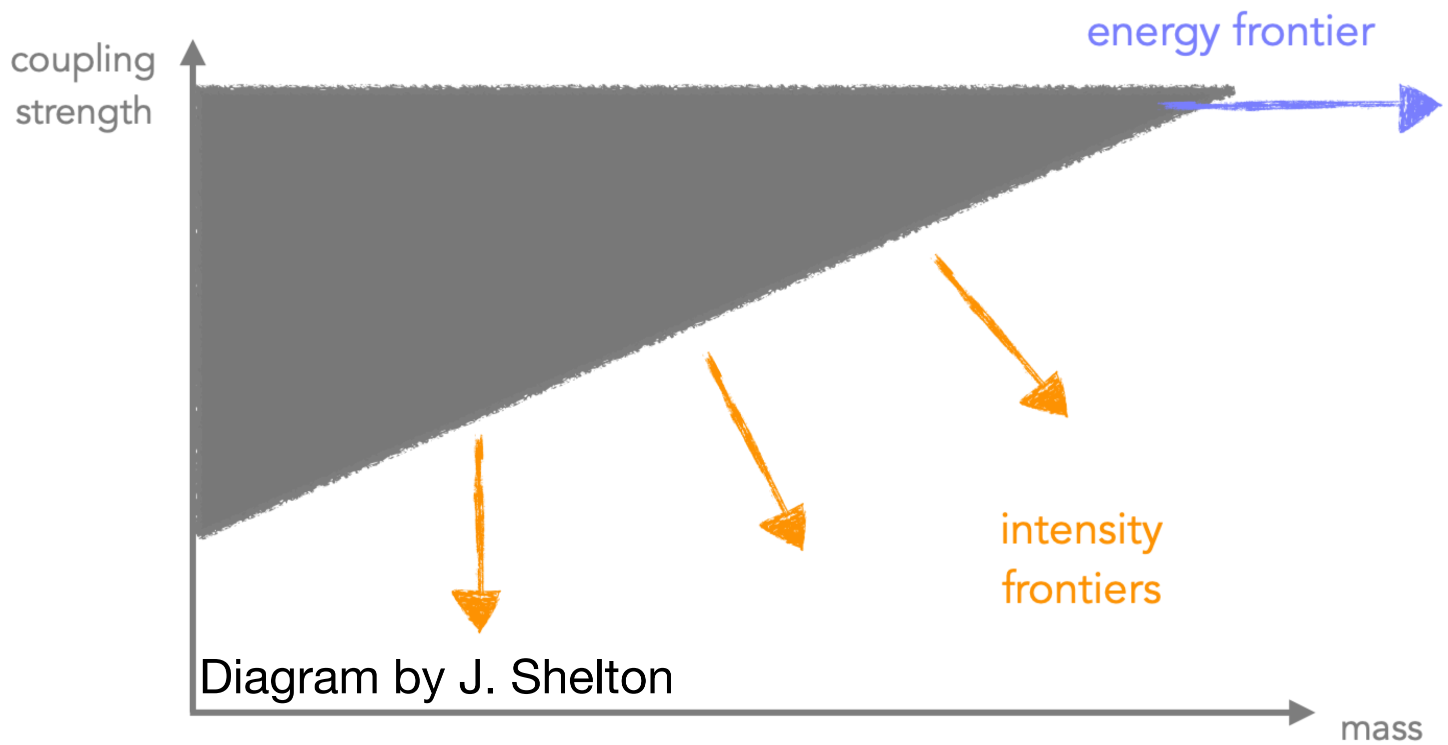


Diagram by J. Shelton

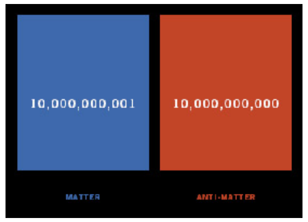
- LLPs arise due to suppressed couplings or small mass splitting
- In this talk, the case of LLPs due to suppressed couplings

- As we prepare for the future colliders we should keep three objectives in mind
  - What is the prime purpose of the said experiment?
  - What other aims it can achieve?
  - Whether we have adequate technology/optimal detector design to fulfil the two above?
- Future (h/Z factories) lepton (ee) colliders prime aim: measurements of properties of the Higgs boson and electroweak precision physics
- Other aims (this talk): searches for long lived particles

Why LLPs?

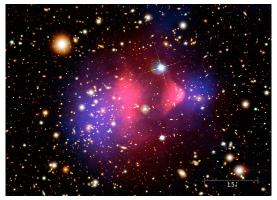
- Generic probe of new physics scenarios
- May help answer following questions:
  - What is the origin of neutrino masses?

  - What caused baryon asymmetry of the Universe?



  - Where is axion?

  - What are dark matter interactions with the Standard Model?



  - Are there extended scalar sectors beyond the Standard Model?
  - Are there extended gauge sectors beyond the Standard Model?

Future colliders ee options

arXiv:2011.04725

Higgs run

Collider	$\sqrt{s}$ [GeV]	$\int \mathcal{L}$ [ab^{-1}]	σ_{Zh} [fb]
FCC-ee	240	5	193
ILC	250	2 (pol)	297
CLIC-380	380	1 (pol)	133
CEPC	240	5.6	193

Z pole run

Collider	$\sqrt{s}$ [GeV]	$\int \mathcal{L}$ [ab^{-1}]	N_Z
FCC-ee	m_Z	150	6.5×10^{12}
CEPC	m_Z	16	6.9×10^{11}

- Limited centre of mass energy, however extremely clear environment
- In this talk, the case of LLPs due to suppressed couplings
- Low energy colliders, charge neutral LLPs (light SM charged new physics constrained)

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	$\frac{a}{f_a} F_{\mu\nu}\tilde{F}^{\mu\nu}$, $\frac{a}{f_a} G_{i,\mu\nu}\tilde{G}^{\mu\nu}_i$, $\frac{\partial_\mu a}{f_a}\overline{\psi}\gamma^\mu\gamma^5\psi$
Sterile Neutrino, N	$y_N LHN$

Future colliders ee as Z factory

Z pole run

Collider	$\sqrt{s}$ [GeV]	$\int \mathcal{L}$ [ab^{-1}]	N_Z
FCC-ee	m_Z	150	6.5×10^{12}
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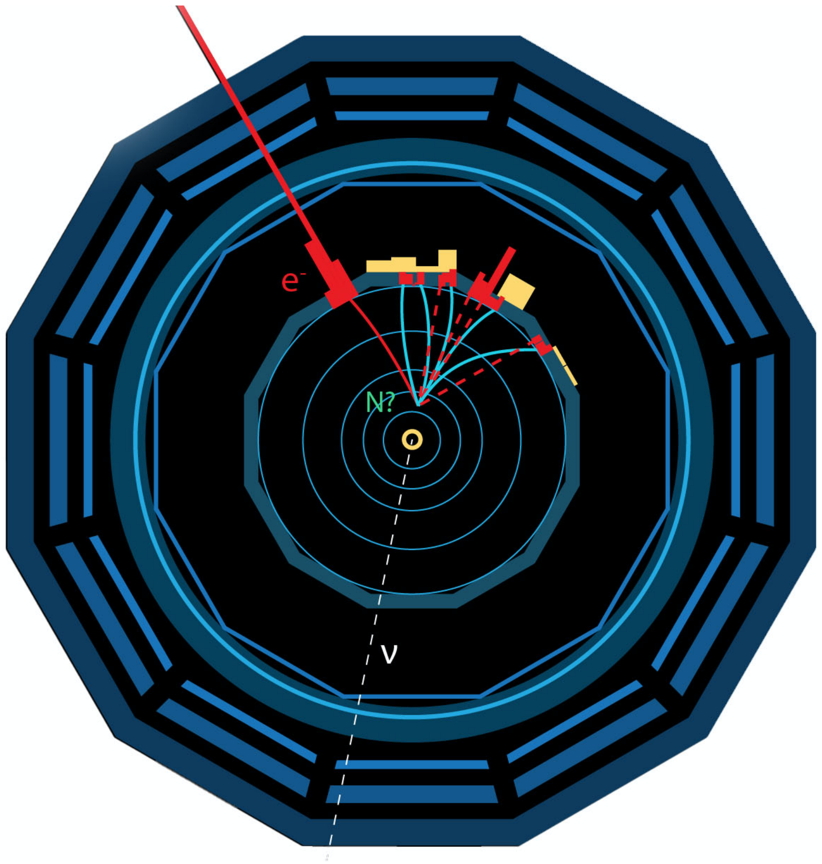
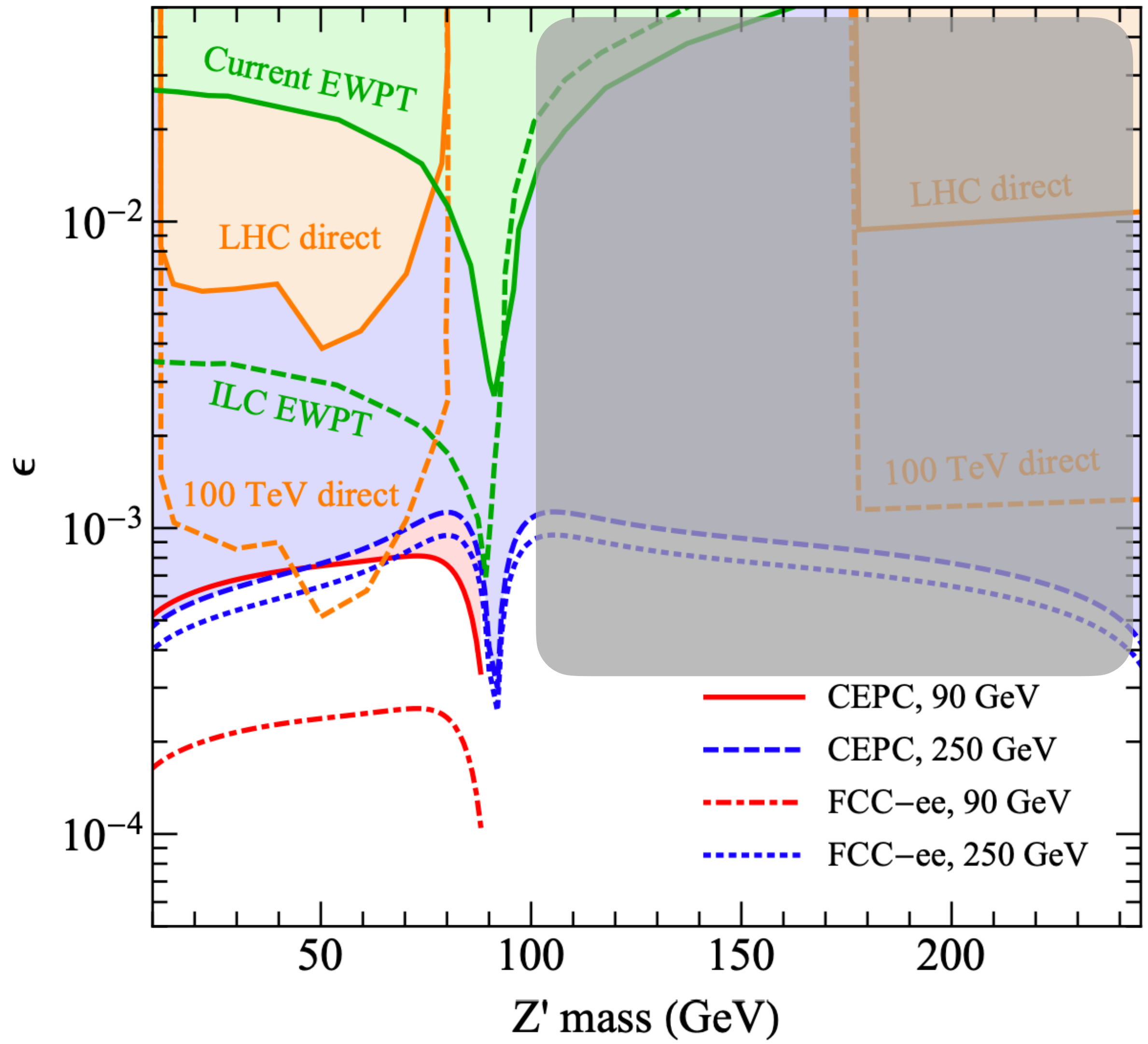


- Limited centre of mass energy, huge luminosity
- Excellent possibility to study light new physics
- Use Z or γ mediated production channels

Vector portal

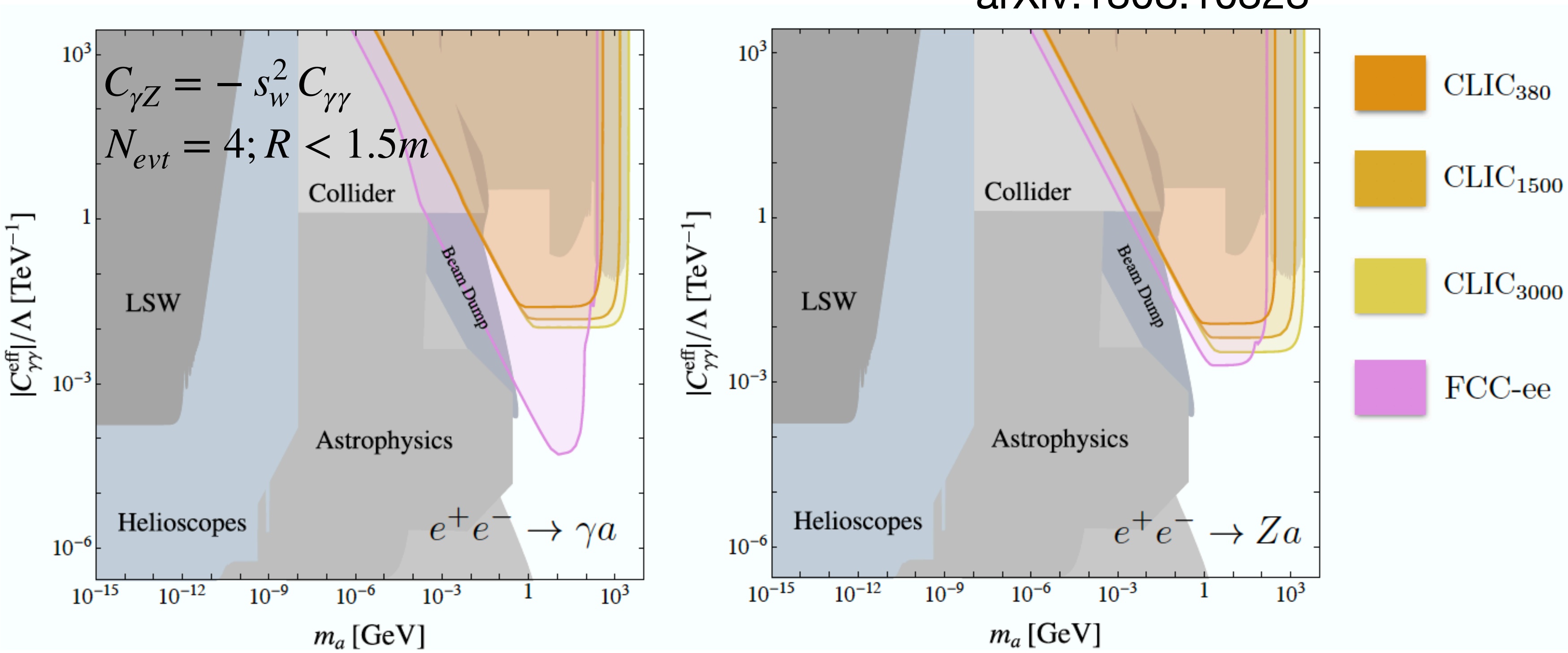
arXiv:1503.07209

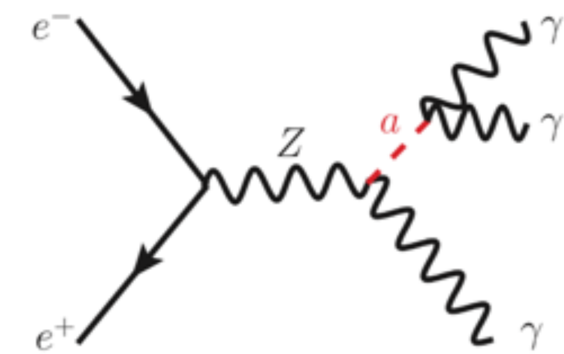


- Radiative return as a probe for new physics: $e^+e^- \to Z'\gamma, Z' \to f\bar{f}$
- Potential to surpass even 100 TeV collider for portal masses less than 100 GeV

Axion/ALPs portal

arXiv:1808.10323





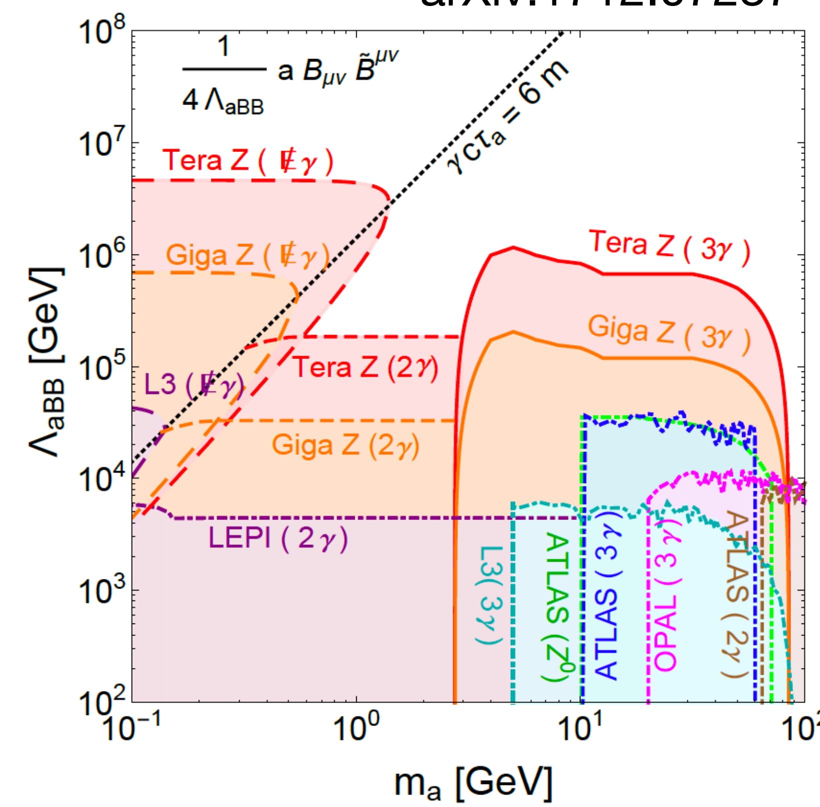
$$\mathcal{L}_{\rm eff} \ni e^2\, C_{\gamma\gamma}\, \frac{a}{\Lambda}\, F_{\mu\nu}\, \tilde{F}^{\mu\nu} + \frac{2e^2}{s_w c_w}\, C_{\gamma Z}\, \frac{a}{\Lambda}\, F_{\mu\nu}\, \tilde{Z}^{\mu\nu} + \frac{e^2}{s_w^2 c_w^2}\, C_{ZZ}\, \frac{a}{\Lambda}\, Z_{\mu\nu}\, \tilde{Z}^{\mu\nu}$$

- In broken phase

$$C_{\gamma\gamma} = C_{WW} + C_{BB} \qquad C_{\gamma Z} = c_w^2\, C_{WW} - s_w^2\, C_{BB} \qquad C_{ZZ} = c_w^4\, C_{WW} + s_w^4\, C_{BB}$$

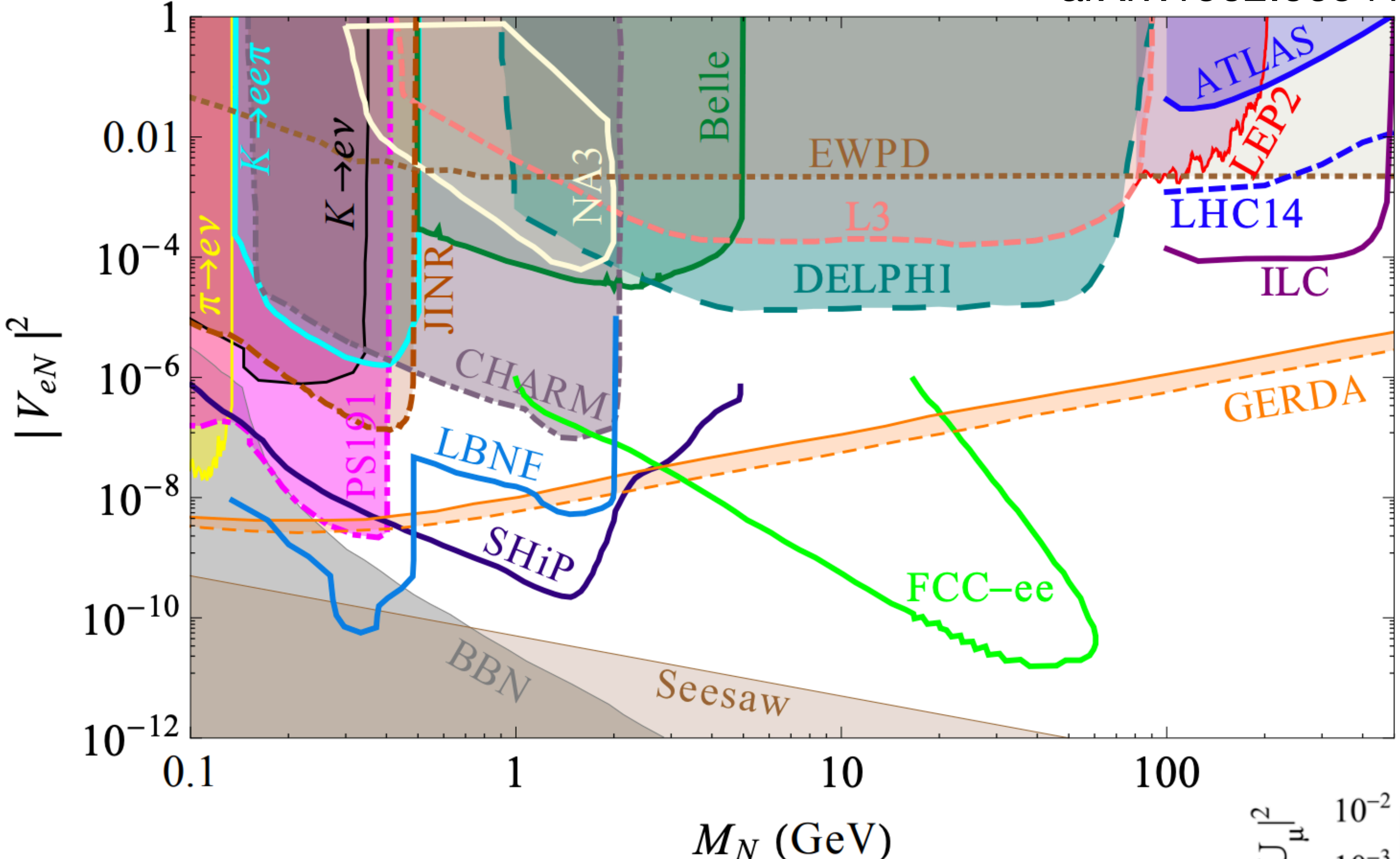
- Significantly larger sensitivity for $e^+e^- \to \gamma a$ compared to $e^+e^- \to Za$
- CLIC probes significantly larger messes due to higher centre-of-mass energy

arXiv:1712.07237

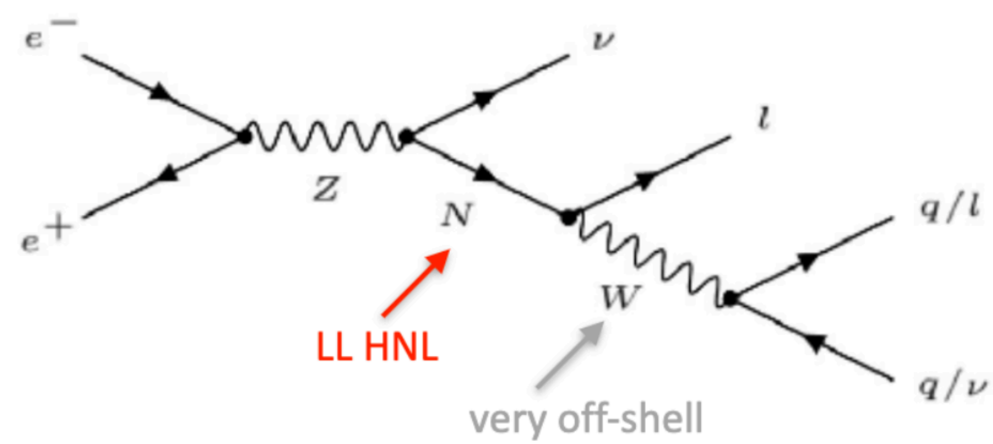


Sterile neutrinos/Heavy neutral leptons

arXiv:1502.06541

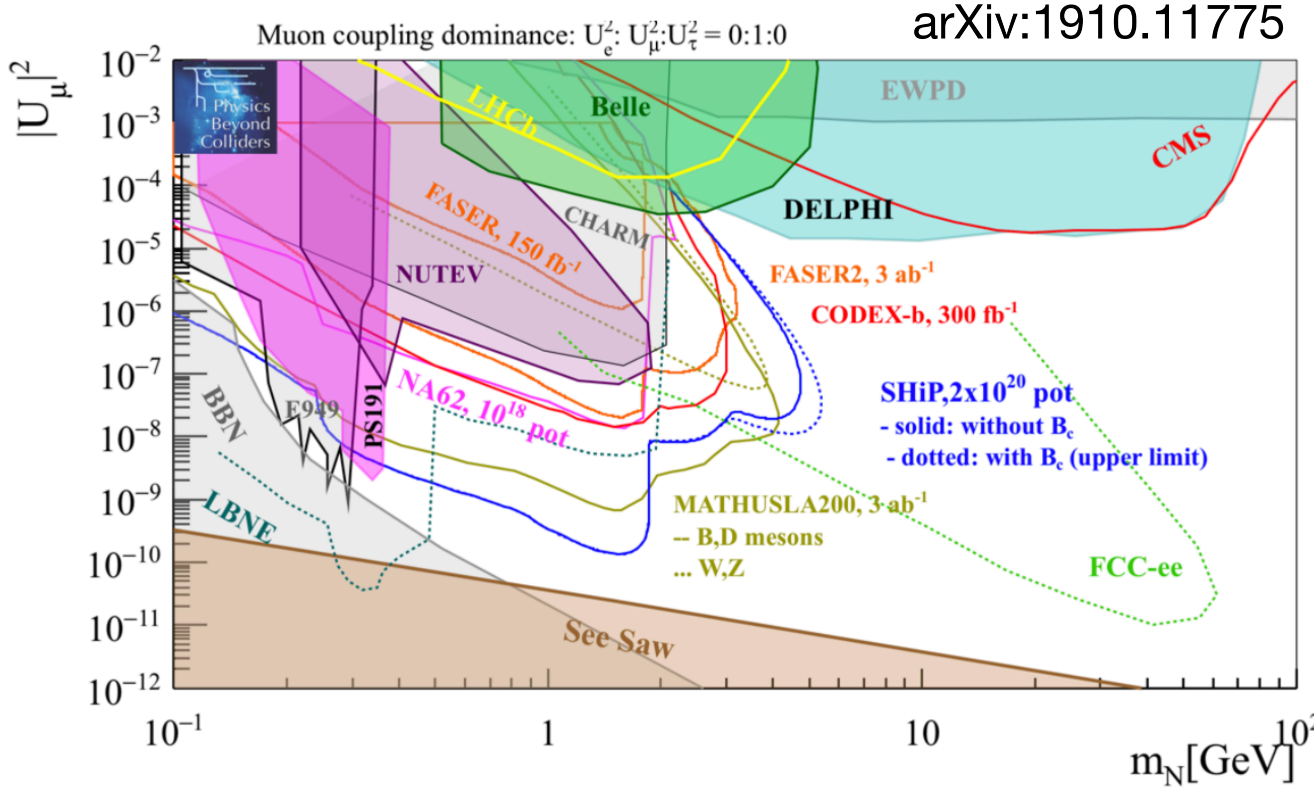


See also talk by Oliver Fischer

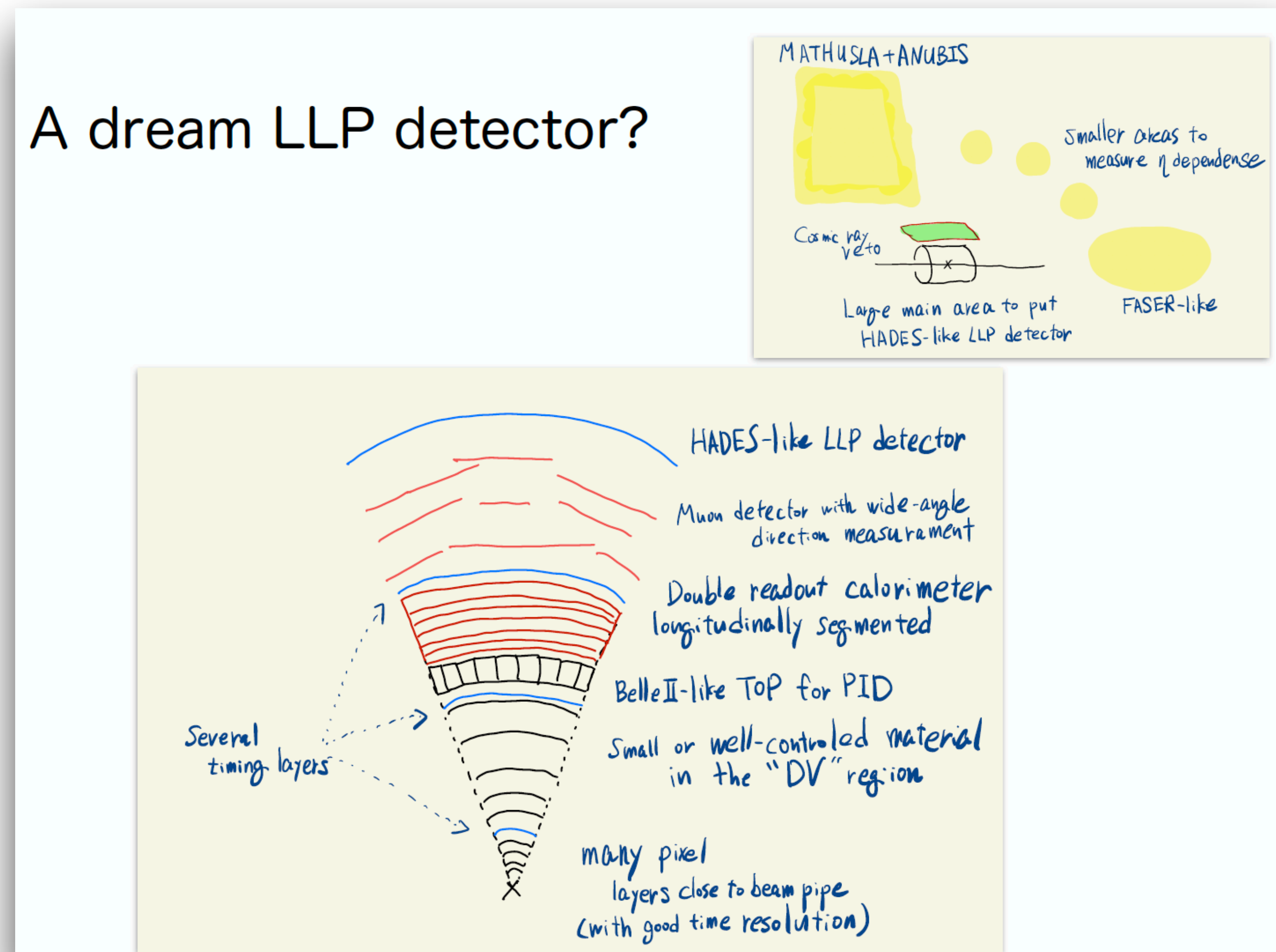


- Heavy neutrino: poster child for LLP
- Simplest case of one sterile neutrino
- Complementarity with $0\nu\beta\beta$
- Several options in lepton flavours to reduce backgrounds

arXiv:1910.11775



- Design future detectors optimised for prompt physics (after all this is the prime target) and use them for LLP studies: not easy we know from LHC
- Incorporate LLP search/discovery prospects right in design of detectors

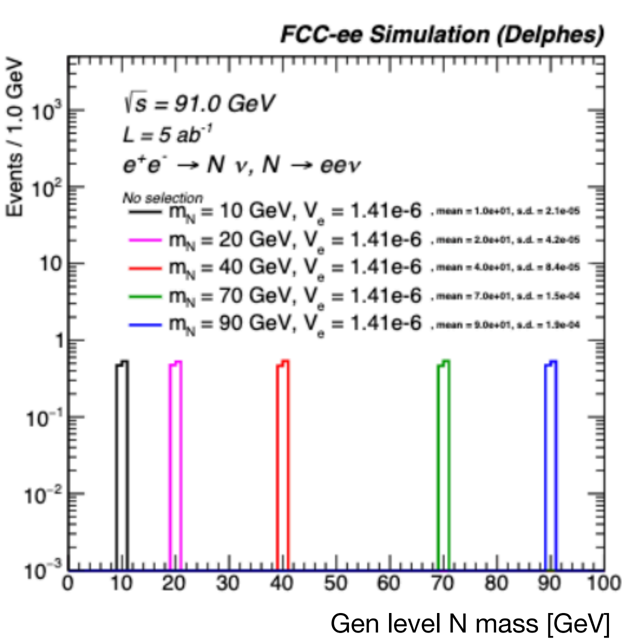


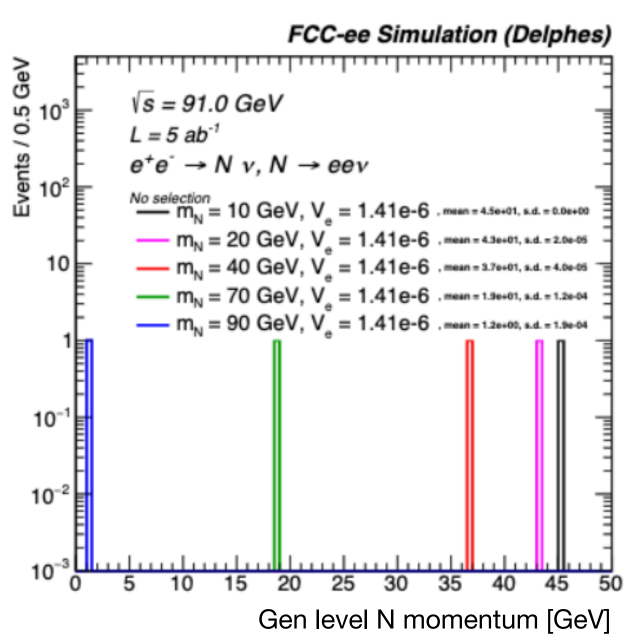
It is a good time to plan our ***dream LLP detectors***, following Ryu Sawada's first example at the LLP workshop in November-2020 (link)

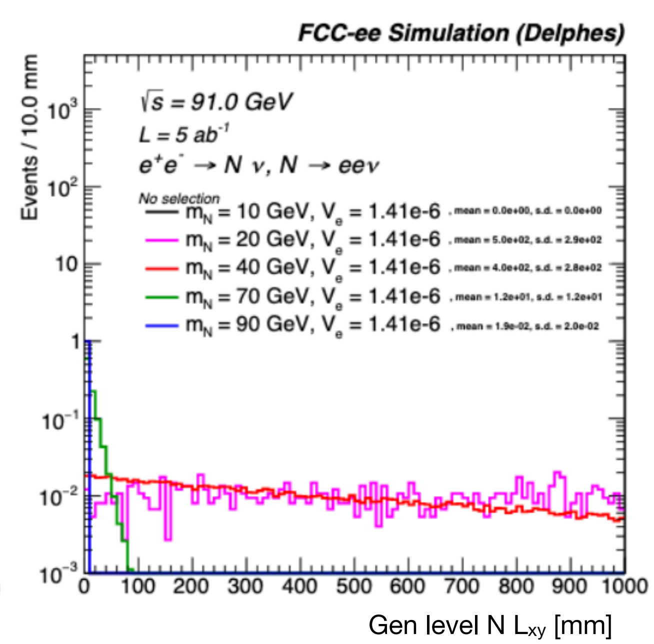
Reality check

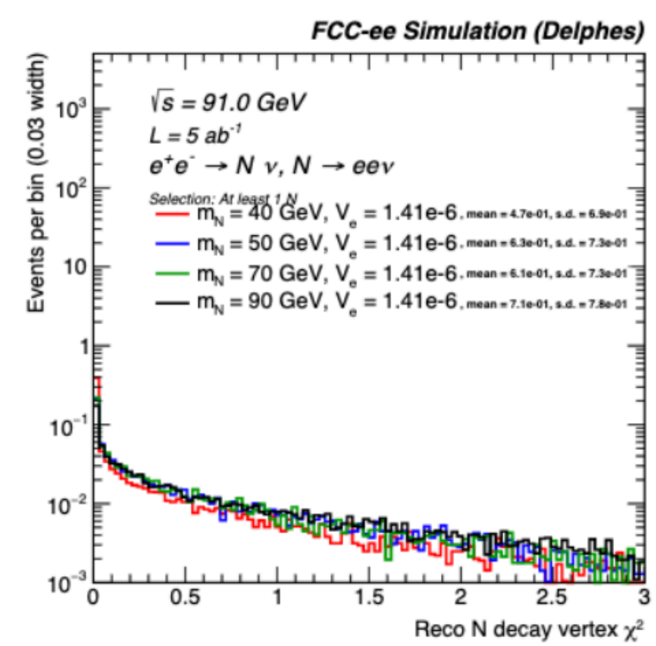
- How well will the current design reach the theory projections?: ongoing FCC-ee snowmass project
- Necessary to perform studies about detector design and capabilities
- Need to port theory technology to KEY4HEP technology — See talk by Dr. Andre Sailer
- Porting of HNL as one of the BSM LLP physics scenario ongoing
- Capable of making plots, elementary vertex reconstruction studies
- Opportunities for short student projects, useful for larger community — See master thesis Rohini Sengupta
- More to come in the future, stay tuned

Plots by J. Alimena (preliminary)



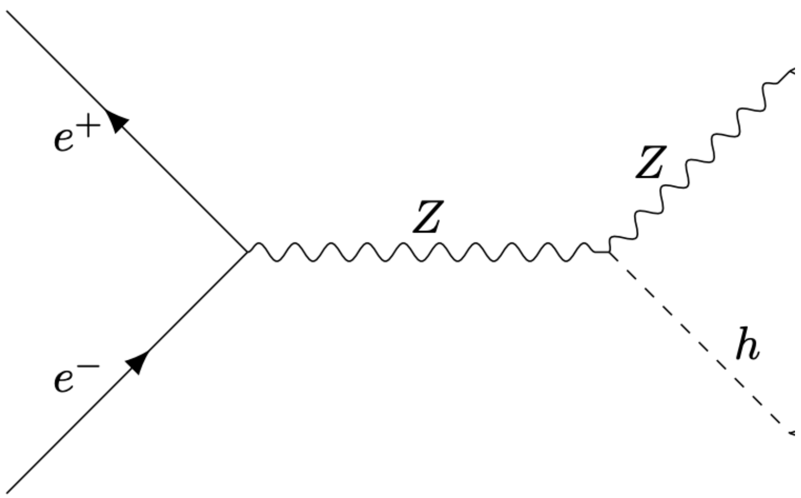






Lepton colliders as Higgs factory

- One possibility is to use Higgs invisible decay width to constrain Higgs couplings to new physics
- Better job can be done if Higgs decays to new visible objects



Higgs run

Collider	$\sqrt{s}$ [GeV]	$\int \mathcal{L}$ [ab^{-1}]	σ_{Zh} [fb]
FCC-ee	240	5	193
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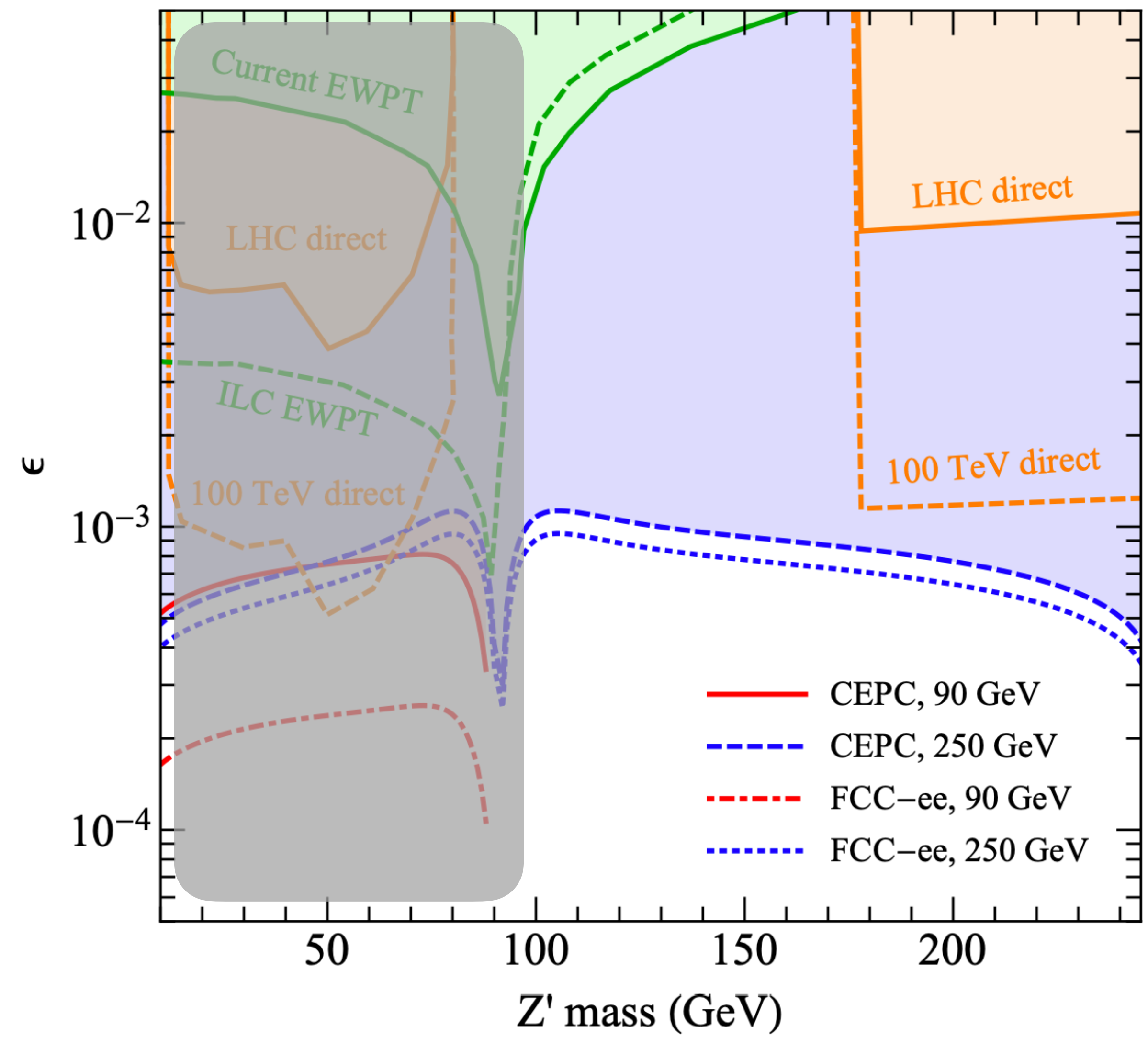
CLIC-380	380	1 (pol)	133
CEPC	240	5.6	193

- Once again multiple options at different centre of mass energies

Vector portal

arXiv:1503.07209



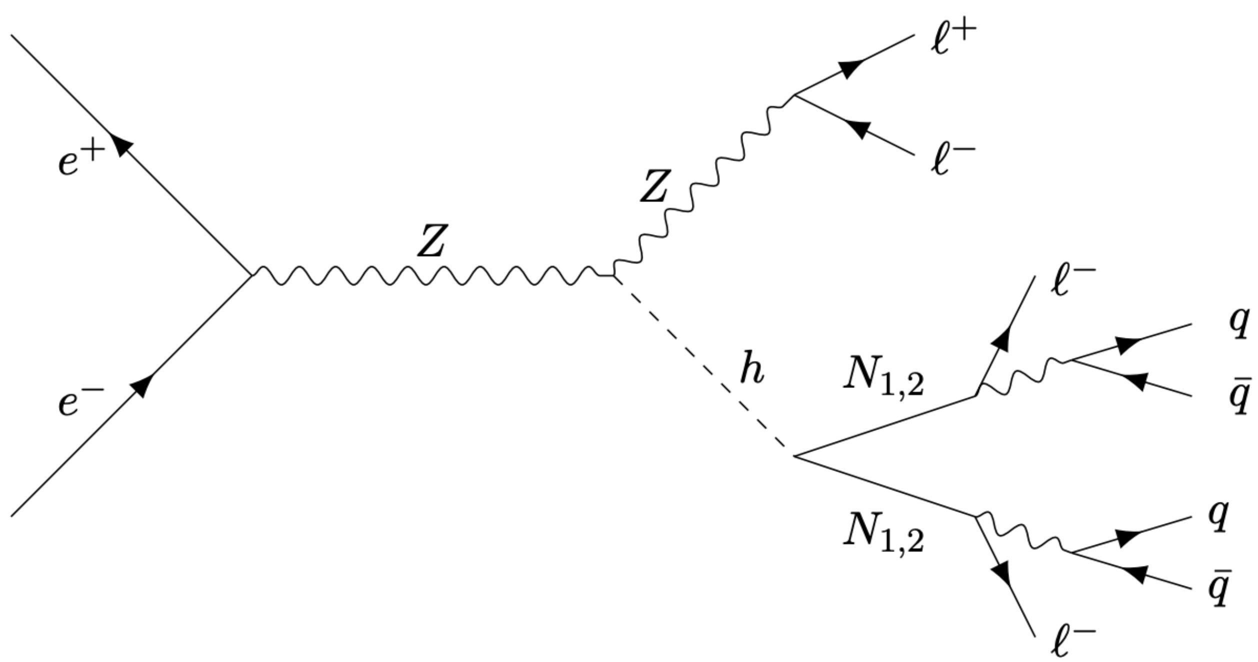
- Excellent reach for heavier Z’ masses as well
- CEPC and FCC-ee potentials are similar

Heavy neutral lepton

arXiv:2011.04725

- HNLs can be incorporated in a variety of SM extensions
- The minimal model is attractive and should certainly be explored
- Alternative possibility: HNL production happens via some effective operators

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \bar{N}\partial\!\!\!/ N - \bar{L}_L Y_\nu \tilde{H} N - \frac{1}{2} M_N \bar{N}^c N + \sum_{n>4} \frac{\mathcal{O}^n}{\Lambda^{n-4}} + h.c.$$



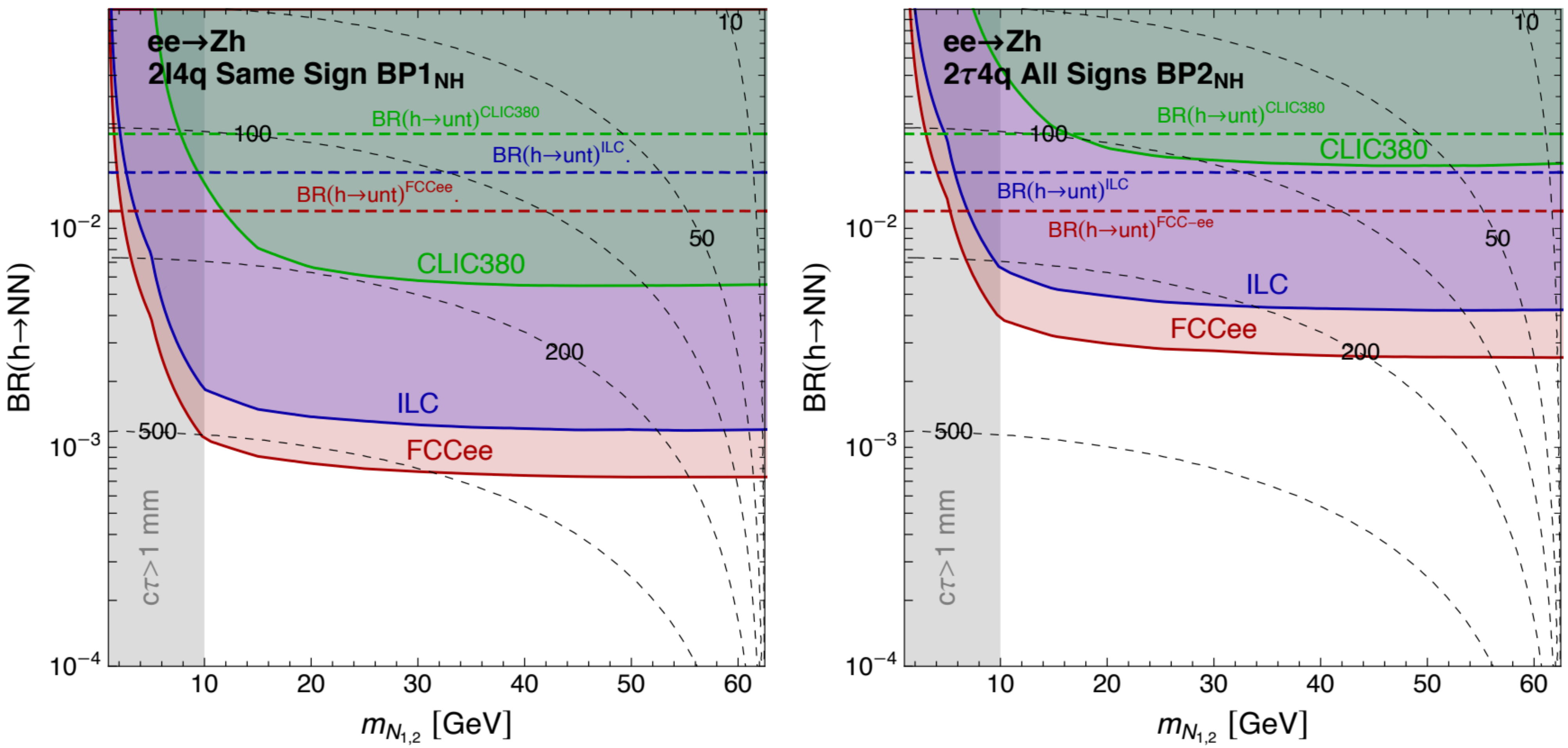
$$\mathcal{O}_W = \alpha_W (\bar{L}^c \tilde{H}^*)(\tilde{H}^\dagger L) \ ,$$
$$\mathcal{O}_{NH} = \alpha_{NH} (\bar{N}^c N)(H^\dagger H) \ ,$$
$$\mathcal{O}_{NB} = \alpha_{NB} \bar{N}^c \sigma^{\mu\nu} N B_{\mu\nu} \ ,$$

$$\Gamma(h \to \bar{N}_i^c N_i) = \frac{1}{2\pi} \frac{v^2}{\Lambda^2} m_H \beta_N^3 (\alpha_{NH}^{ii})^2 \ ,$$

$$\beta_N = \sqrt{1 - \frac{4m_N^2}{m_H^2}} \ .$$

Some sensitivity estimates

arXiv:2011.04725

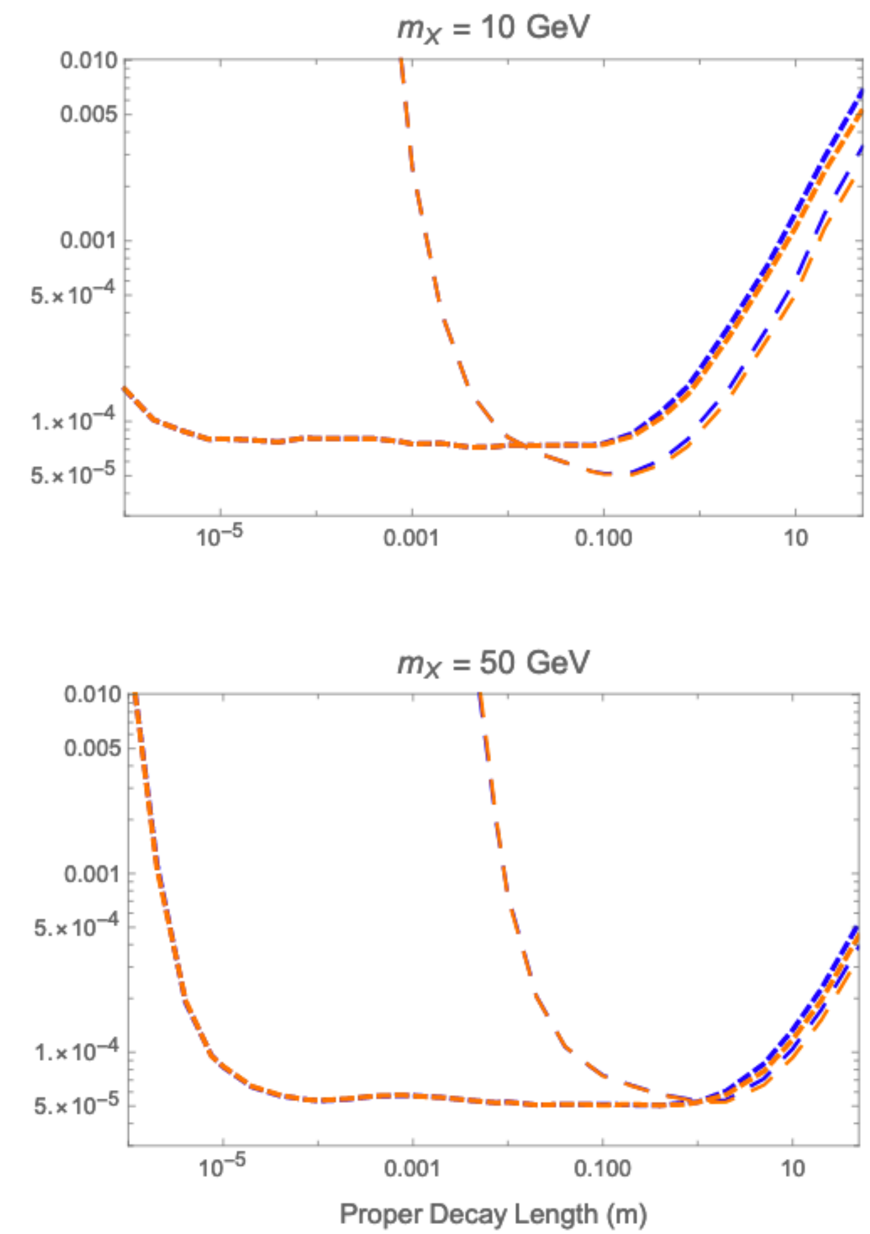


- Two benchmarks corresponding to different SM neutrino flavour mixing patterns
- Dashed lines correspond to the cutoff scale lambda
- Promising limits
- Favourable scenarios for cut-off scale above 500 GeV

Higgs exotics

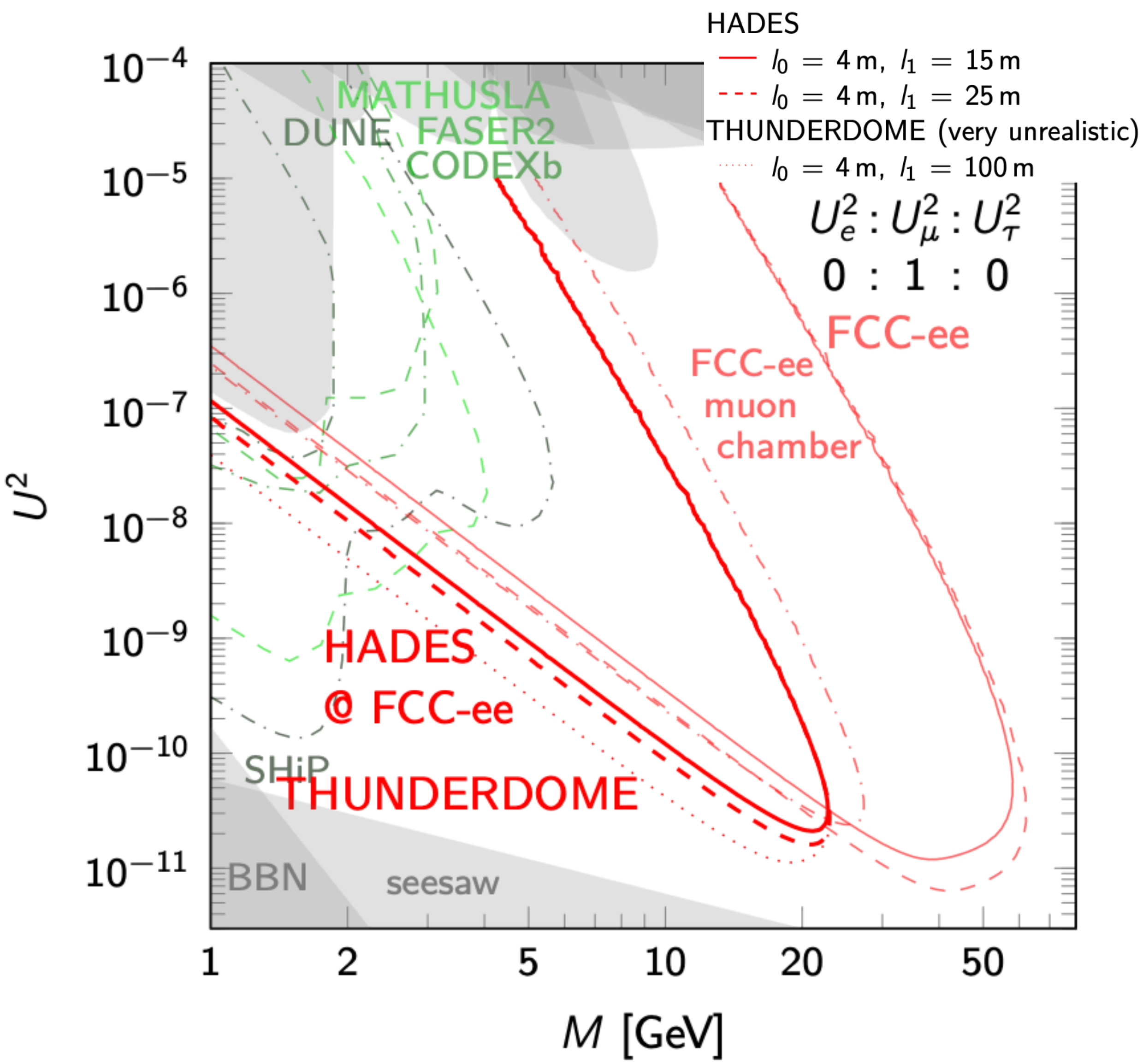
See also talk by Inbar Savoray, Yulei Zang

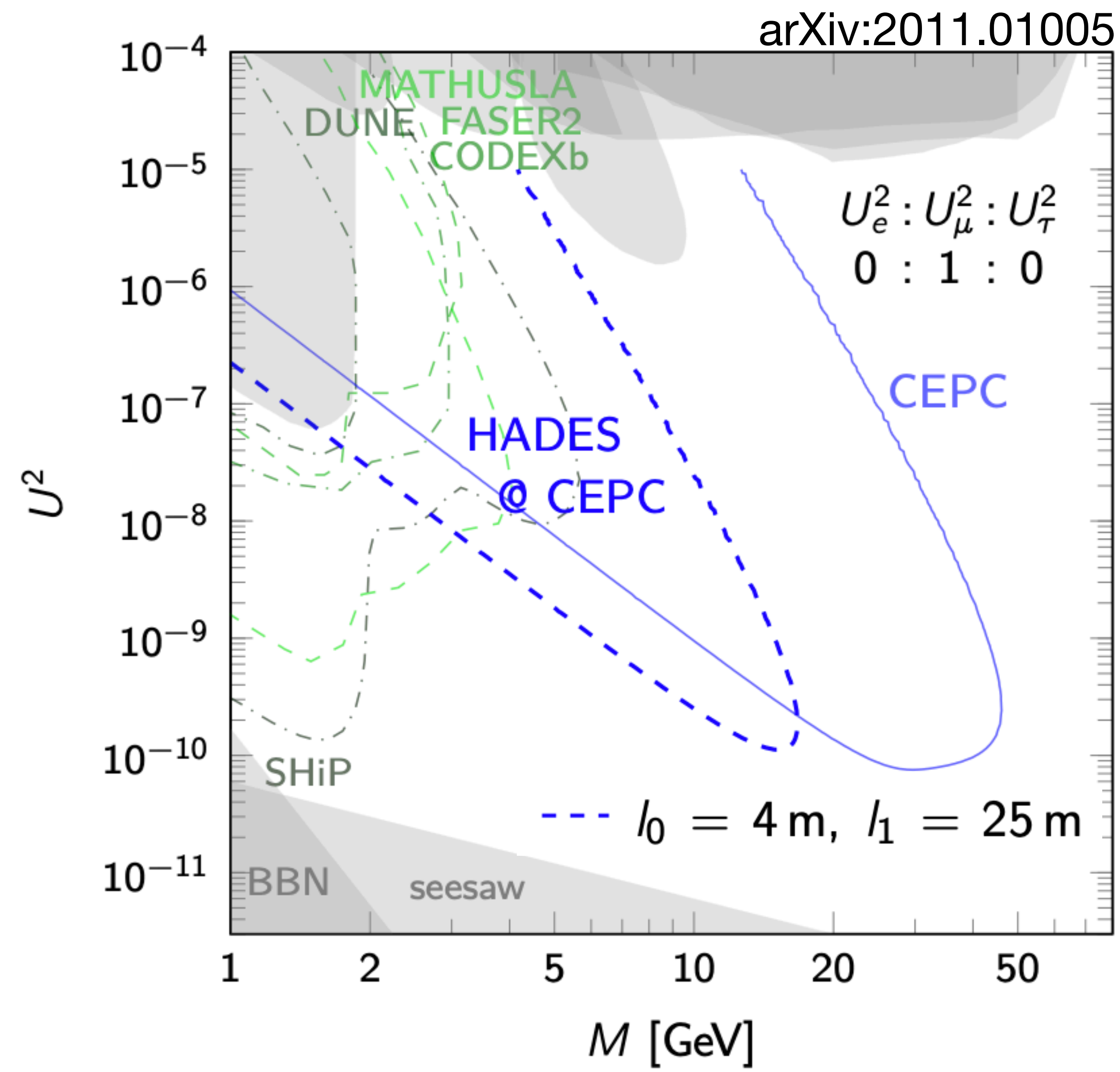
- Higgs precision physics one of the main goals
- $h \to XX$ a poster child of exotic Higgs benchmarks
    - **Twin Higgs** models with displaced exotic Higgs boson decays, **Hidden Valley** models with neutral, long-lived particles that the Higgs boson can decay to (arXiv:1812.05588)
    - Long-lived particle signals arising from Higgsinos or exotic Higgs decays (arXiv:1712.07135)
- Particularly useful for lighter X masses



Slide by R. Gonzalez Suarez

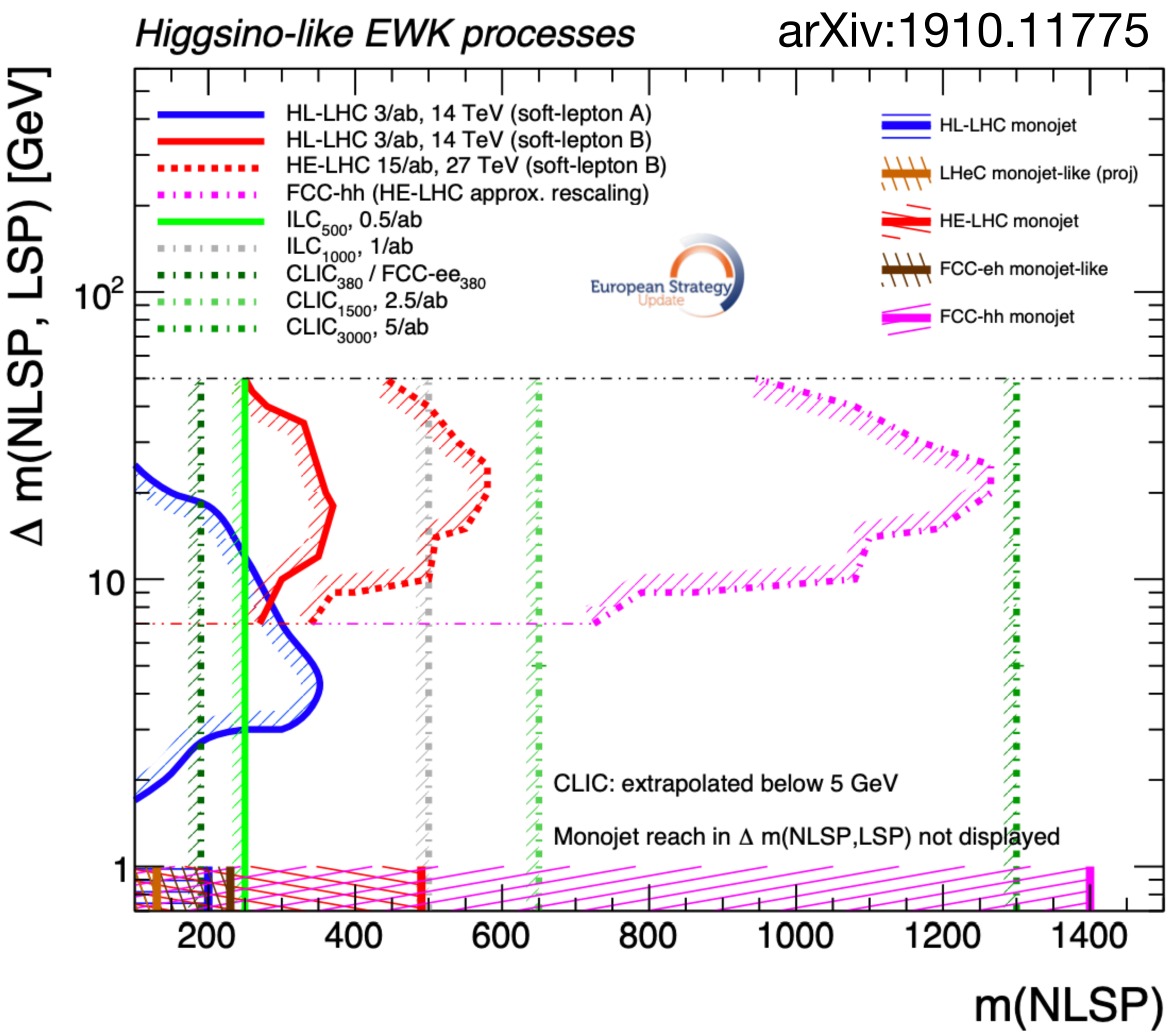
Beyond ‘traditional’ detectors

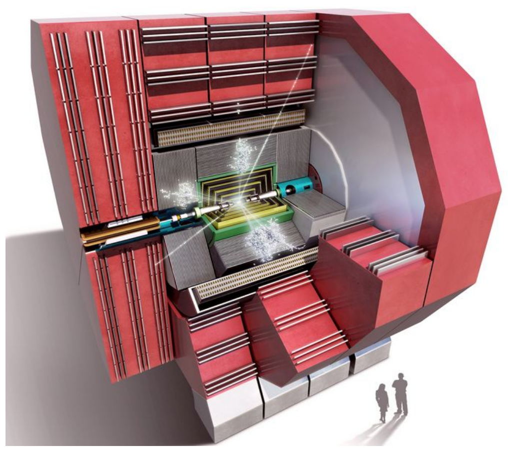




- Could we build/propose lifetime frontier/forward physics detectors at lepton colliders?
- HADES/HECATE detector proposes to use the cavern to build a new lifetime frontier detector
- Can help improve reach of LLPs, here case study of HNL

Beyond Higgs and Z factories

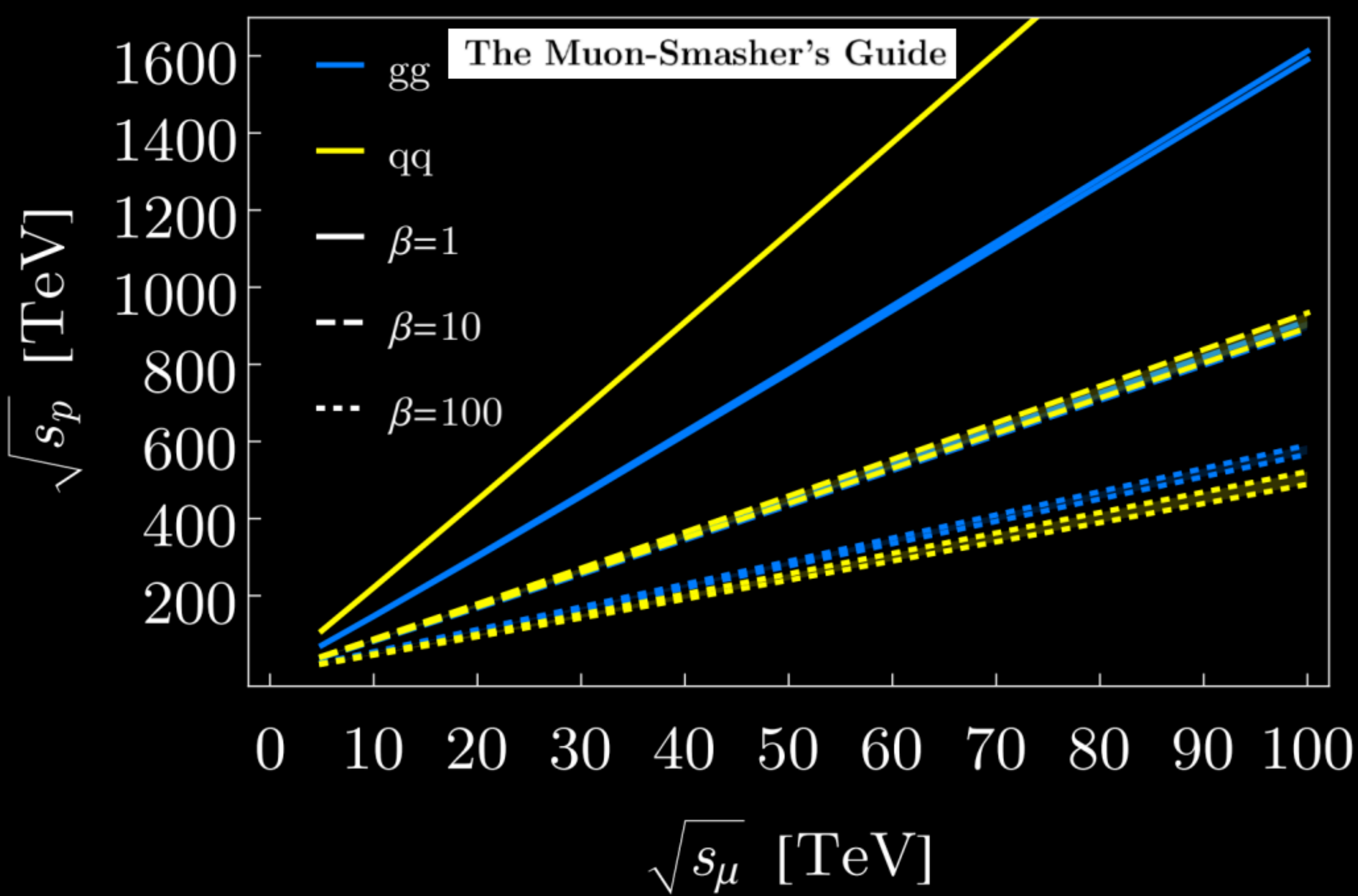




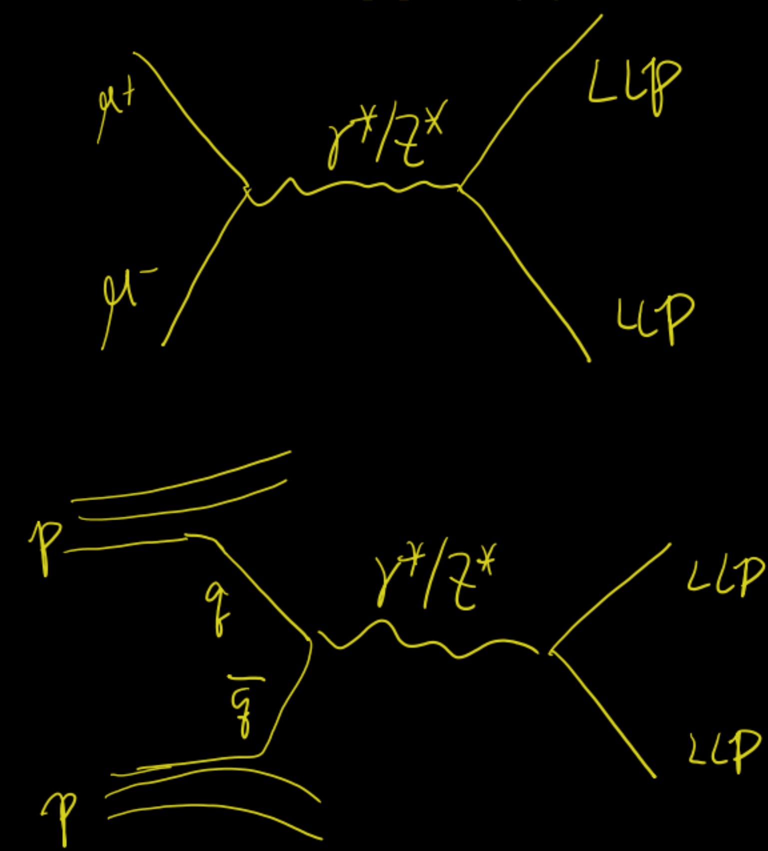
- Lepton colliders beyond Higgs and Z factories bring in a wealth of new physics scenarios and their LLP signatures
- Case in point : disappearing tracks due to long lived chargino in susy scenarios
- CLIC offers competitive limits to FCC-hh

See also discussion at LLP-IX and snowmass discussions

A truly High Energy Machine



$\beta \equiv \sigma_{pp}/\sigma_{\mu\mu}$



10+ TeV MuC outperforms 100 TeV collider in almost every aspect

(except for dijet resonances; particles only color charged, no EW charges)

For electroweak states, already winning if MuC have 3+ TeV energy

MuC LLP LLP9 Zhen Liu 05/28/2021 10

Conclusions

- Future lepton colliders bring an exciting opportunity to test new physics
- Main advantages: High luminosity, high center-of-mass energy, clean environment
- We need to identify possible new physics scenarios which can be probed and LLP are one of the possibilities
- Light new LLPs still very much viable and physically motivated
- Work needed to identify interplay of detector capabilities and theoretical studies