# Long lived particles at FCC

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NAWI Graz
Natural Sciences

FWF
Der Wissenschaftsfonds.

UNI GRAZ

# Why, how, where LLPs?

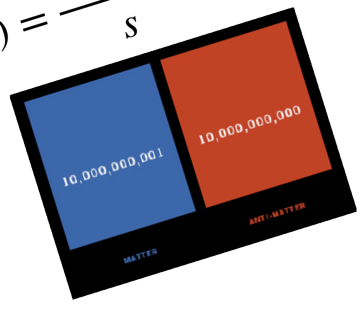
- Answers to a range of unsolved questions can generically lead to LLP

See talk by T. You

$m_\nu \neq 0$

$\theta \frac{g_s^2}{32\pi^2} \tilde{G}_b^{\mu\nu} G_{b\mu\nu}$

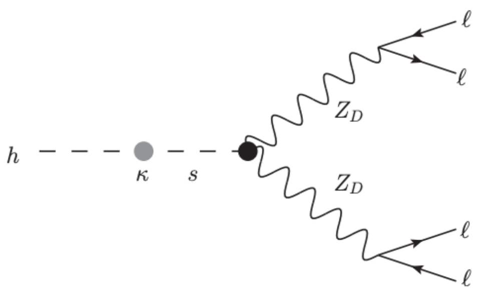
$\eta(b) = \frac{n_b - n_{\bar{b}}}{s} \sim 10^{-10}$



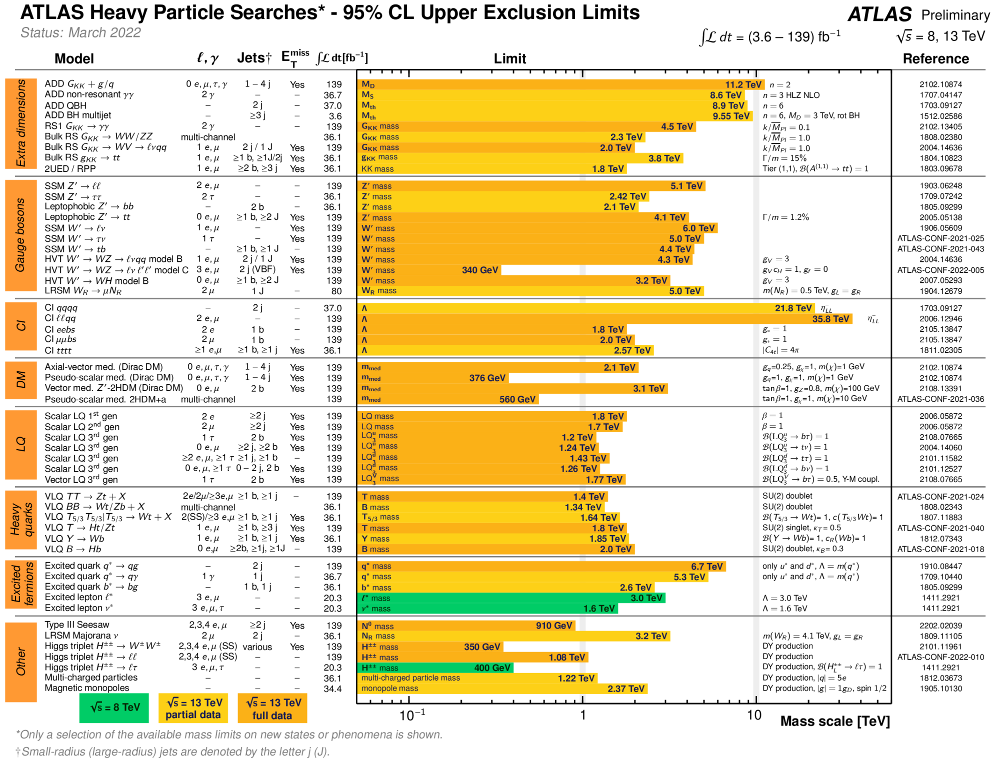
$\Omega h^2 \sim 0.12$

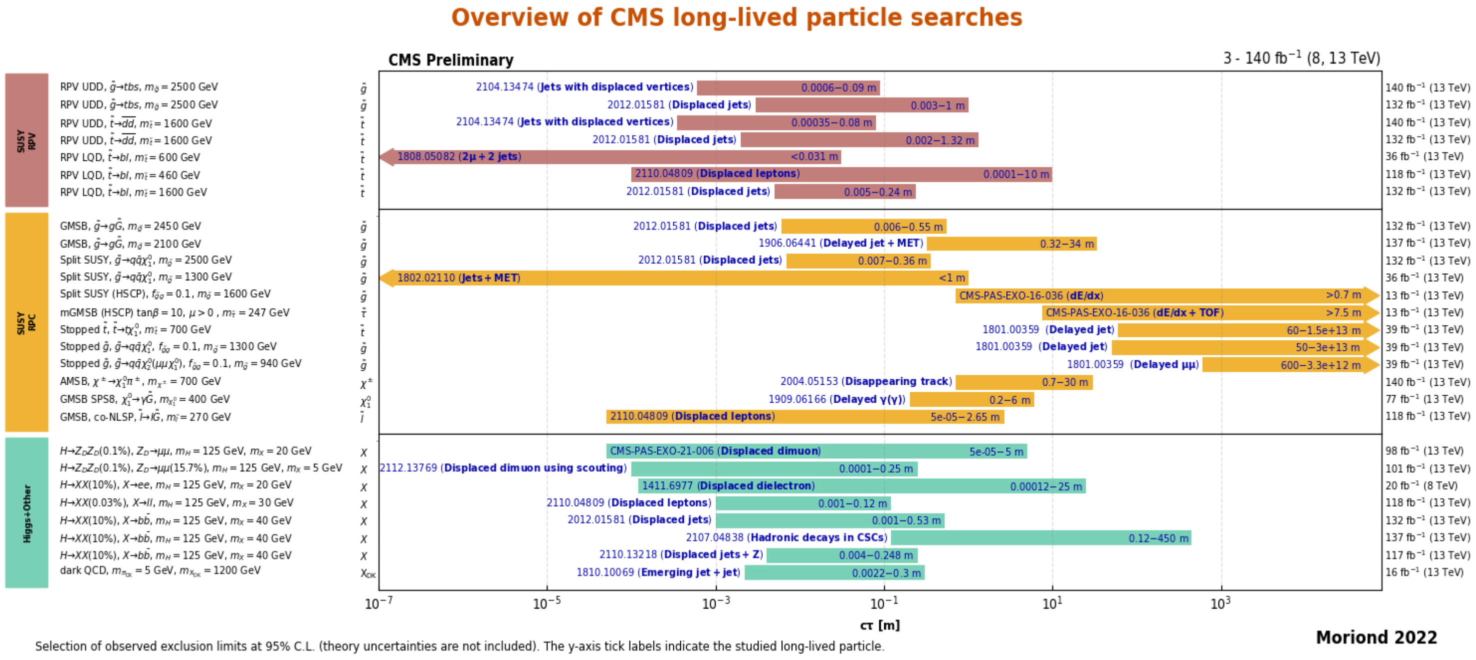
$$\mathcal{L} \subset -\frac{1}{4}\hat{B}_{\mu\nu}\hat{B}^{\mu\nu} - \frac{1}{4}\hat{Z}_{D\mu\nu}\hat{Z}_D^{\mu\nu} + \frac{1}{2}\frac{\epsilon}{\cos\theta}\hat{Z}_{D\mu\nu}\hat{B}^{\mu\nu} + \frac{1}{2}m_{D,0}^2\hat{Z}_D^\mu\hat{Z}_{D\mu}$$

$$V_0(H,S) = -\mu^2|H|^2 + \lambda|H|^4 - \mu_S^2|S|^2 + \lambda_S|S|^4 + \kappa|S|^2|H|^2$$



- LHC BSM program: new physics either heavy and/or feebly coupled and/or leads to soft final states





Selection of observed exclusion limits at 95% C.L. (theory uncertainties are not included). The y-axis tick labels indicate the studied long-lived particle.

# Why, how, where LLPs?

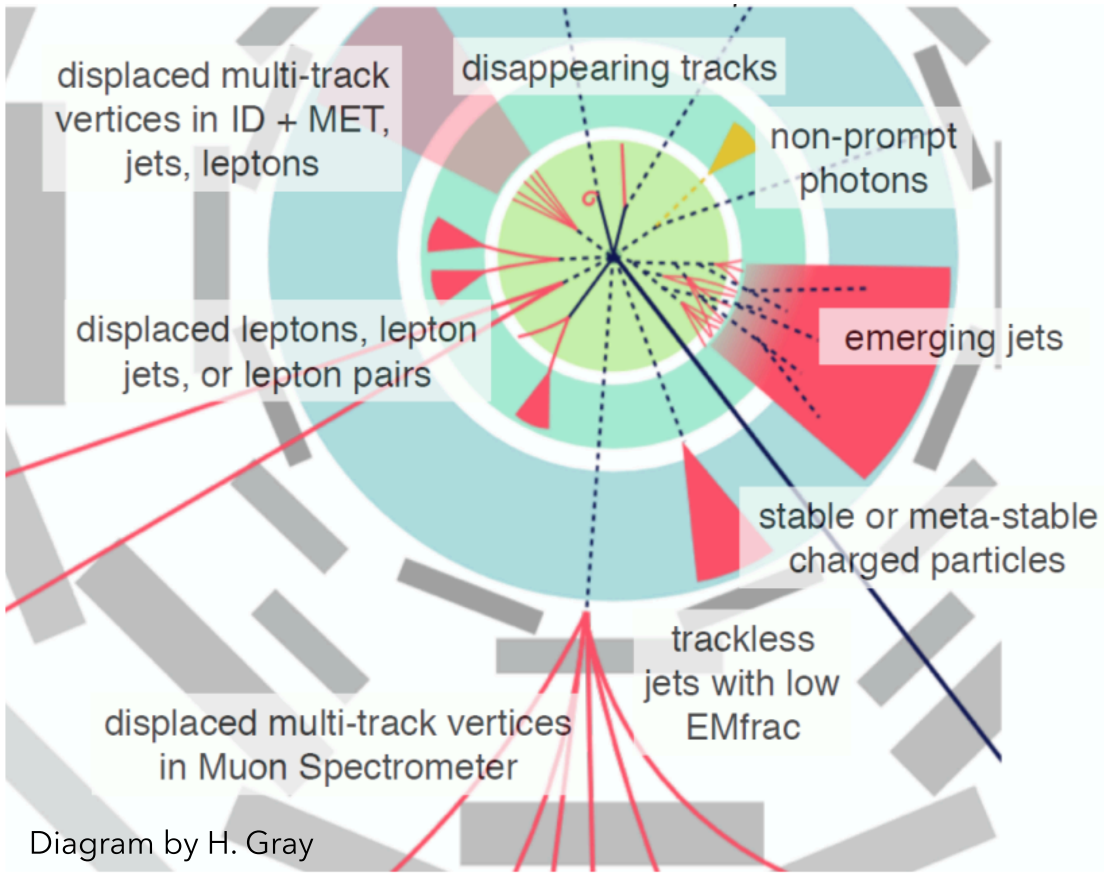


Diagram by H. Gray

- Small couplings or small mass differences generically lead to LLPs
- Exact signature depends on LLP quantum numbers and decay modes → many possibilities, necessary to understand experimental sensitivity to these
- FCC-ee: charge, color neutral initial state → direct production of charge, color neutral BSM particles/ final states
  - Light color, electrically charged BSM particles heavily constrained
  - Consider looking for charge, color neutral particle
  - Displaced vertex signature
- FCC-hh: possible to also probe charged/colored BSM particles
  - Disappearing tracks
  - (Heavy) Heavy stable charged particles, stopped particles, R-hadrons as possible signatures
  - These exotic signatures are not covered in this talk

LLPs can also be looked for in MET and prompt final states

See talk by R. Gonzalez Suarez

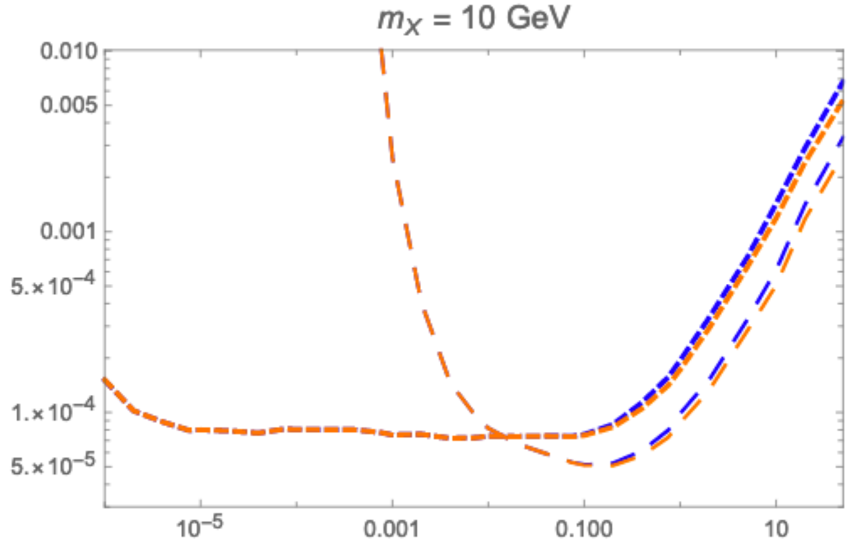
See talks in the morning session

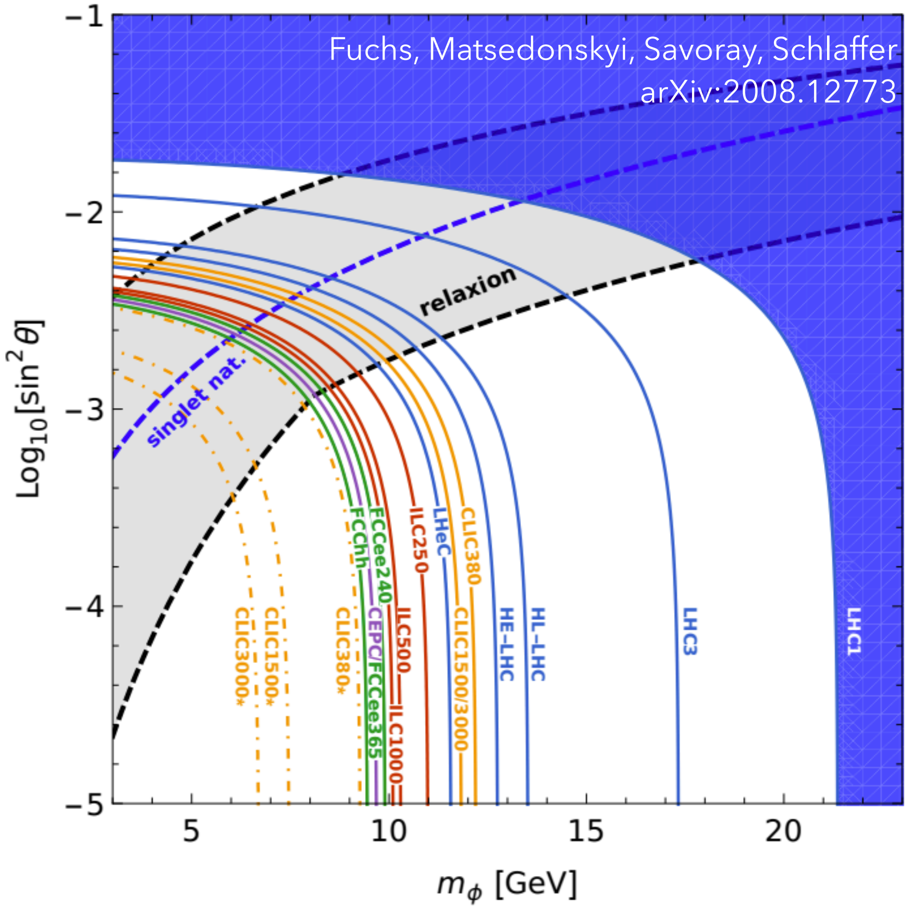
# Higgs exotics

- Higgs precision physics one of the main goals
- Exotic Higgs decays are a window to new physics related to questions from dark matter to naturalness
- $h \to XX$ a poster child of exotic Higgs benchmarks
    - Advantageous in many models to explore light X
    - Multiple available decay modes and complementarity can lead to excellent coverage
    - Also possible to look at $h \to ZX$
    - Mostly considers two body Higgs decays, three body decays are also possible e.g. $h \to NN$
- Physics reach can tell us something about neutral naturalness

See also talk by C. Verhaaren in the LLP informal WG meetings

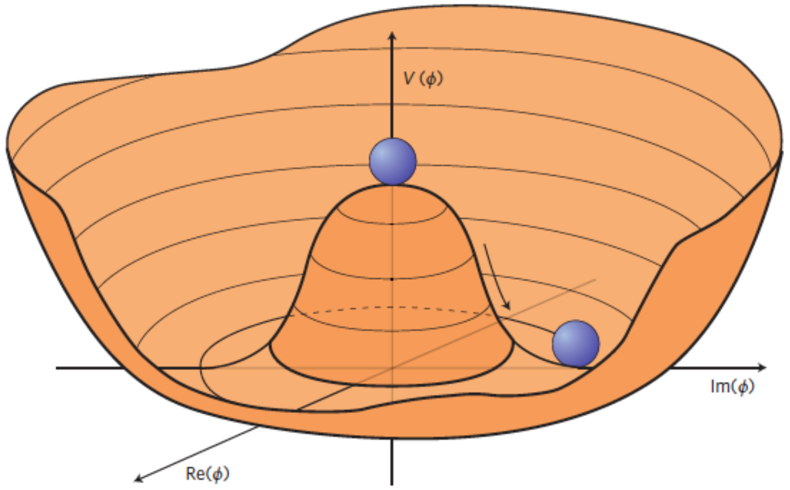
Alipour-Fard, Craig, Jiang, Koren
arXiv:1812.05588




Fuchs, Matsedonskyi, Savoray, Schlaffer
arXiv:2008.12773

# Axion/ALPs

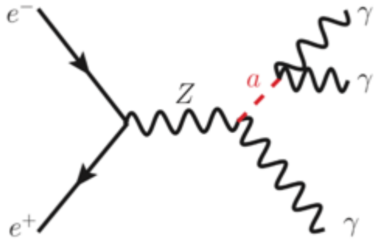
- Are there new spontaneously broken global symmetries in nature?
- Search of ALPs i.e. NGBs associated with breaking of such global symmetries
- Examples:
    - $U(1)_{PQ}$: QCD axion
    - Composite Higgs
    - Supersymmetric pNGB



arXiv:9703409, arXiv:0009290, arXiv:1411.3325, arXiv:1504.06084, arXiv:1604.01127, arXiv:1606.03097, arXiv:0902.1483, arXiv:1312.5330, arXiv:1702.02152, arXiv:2104.11064.

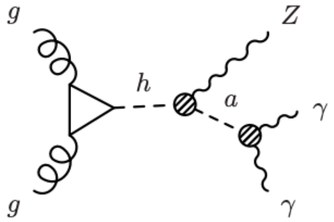
Exotic Z decays

$$\mathcal{L}_{\rm eff}^{D\leq 5} = \frac{1}{2}\,(\partial_\mu a)(\partial^\mu a) - \frac{m_{a,0}^2}{2}\,a^2 + \frac{\partial^\mu a}{f}\,\sum_F \bar{\psi}_F\,\boldsymbol{c}_F\,\gamma_\mu\,\psi_F$$
$$+\, c_{GG}\,\frac{\alpha_s}{4\pi}\,\frac{a}{f}\,G_{\mu\nu}^a\,\tilde{G}^{\mu\nu,a} + c_{WW}\,\frac{\alpha_2}{4\pi}\,\frac{a}{f}\,W_{\mu\nu}^A\,\tilde{W}^{\mu\nu,A} + c_{BB}\,\frac{\alpha_1}{4\pi}\,\frac{a}{f}\,B_{\mu\nu}\,\tilde{B}^{\mu\nu}$$

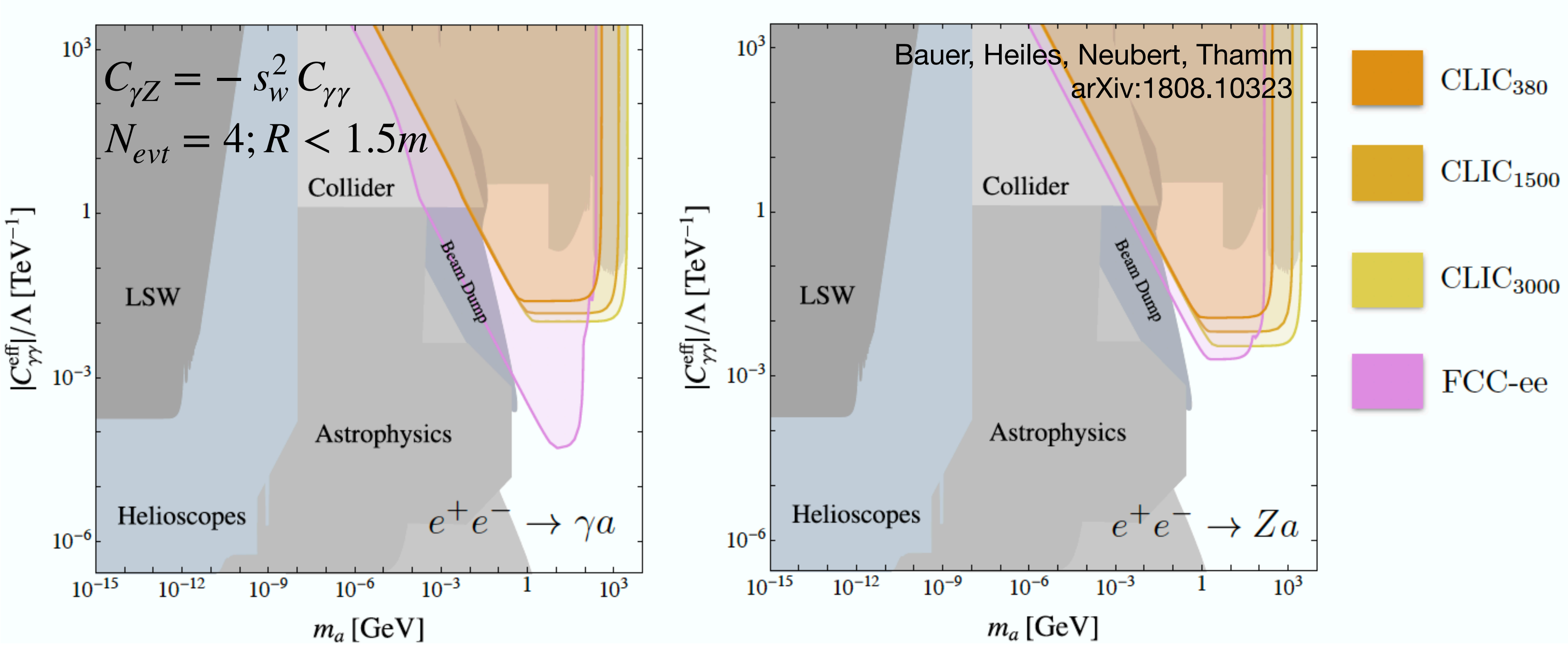


Exotic h decays

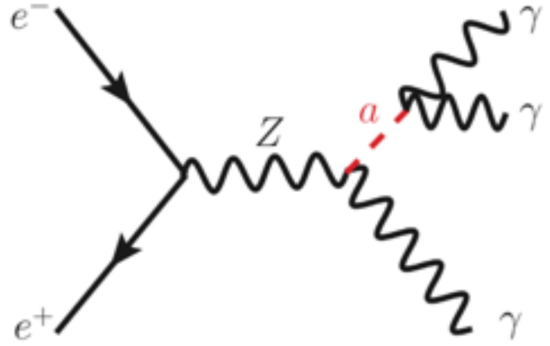
$$\mathcal{L}_{\rm eff}^{D\geq 6} = \frac{C_{ah}}{\Lambda^2}\,(\partial_\mu a)(\partial^\mu a)\,\phi^\dagger\phi + \frac{C_{Zh}}{\Lambda^3}\,(\partial^\mu a)\,\left(\phi^\dagger\,iD_\mu\,\phi + \text{h.c.}\right)\phi^\dagger\phi + \ldots$$



# Axion/ALPs portal: FCC-ee



Bauer, Heiles, Neubert, Thamm arXiv:1808.10323



See also e.g. Liu, Wang, Wang, Xue arXiv:1712.07237

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

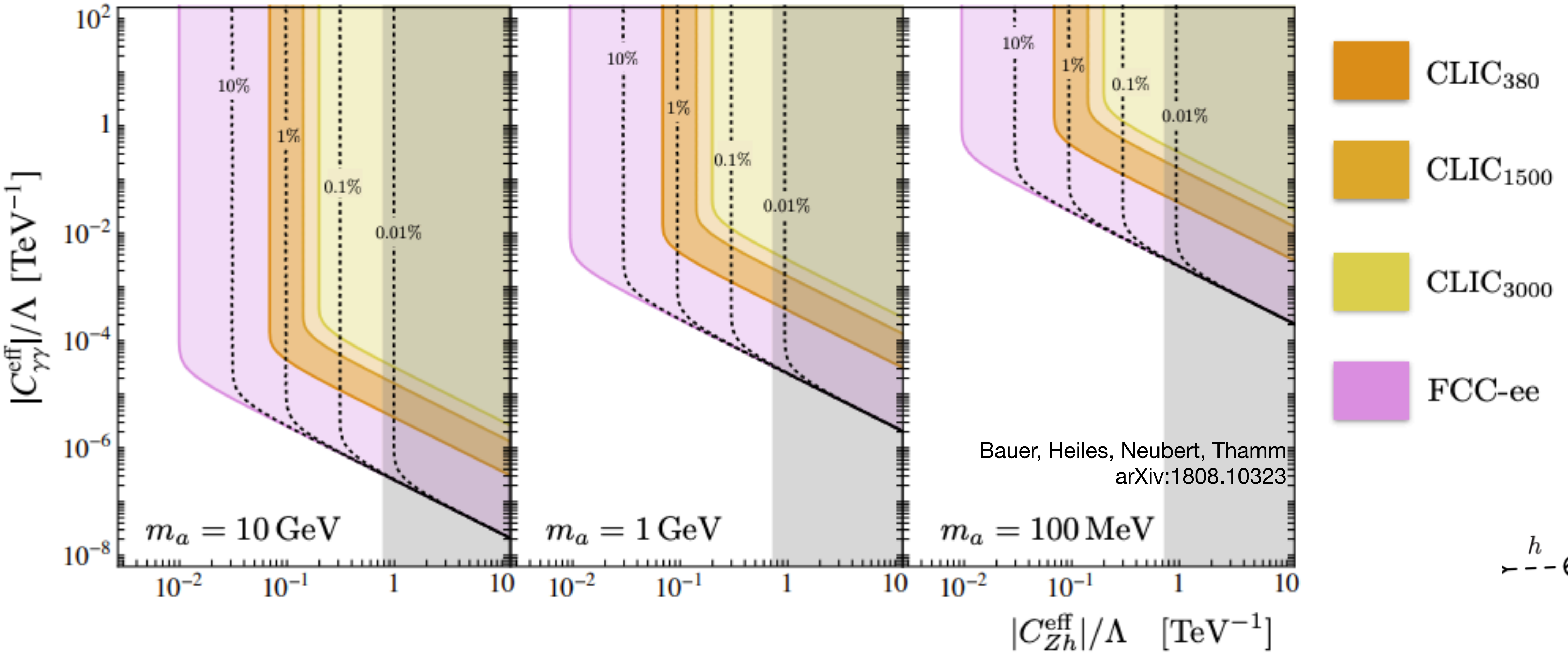
- In broken phase

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

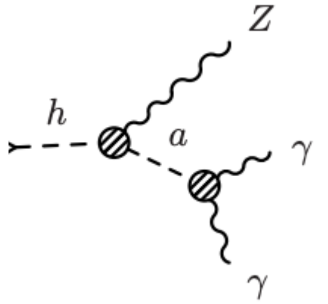
- Significantly larger sensitivity for $e^+e^- \to \gamma a$ compared to $e^+e^- \to Za$
- Low mass axions will lead to collimated photons, will be challenging, necessary to have dedicated studies

# Axion/ALPs portal: FCC-ee

$e^+e^- \to ha \to b\bar{b}\gamma\gamma$

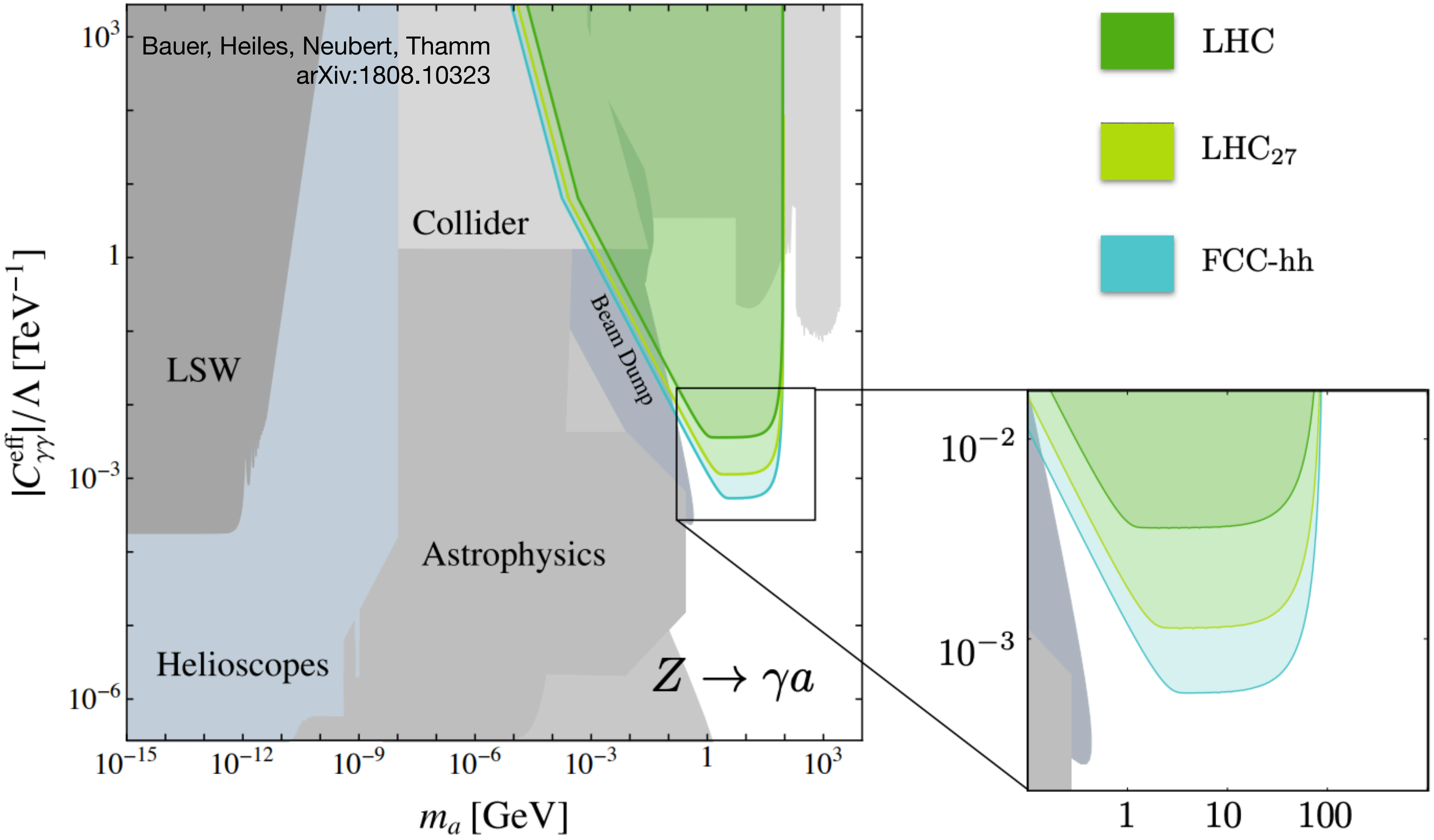


Bauer, Heiles, Neubert, Thamm
arXiv:1808.10323



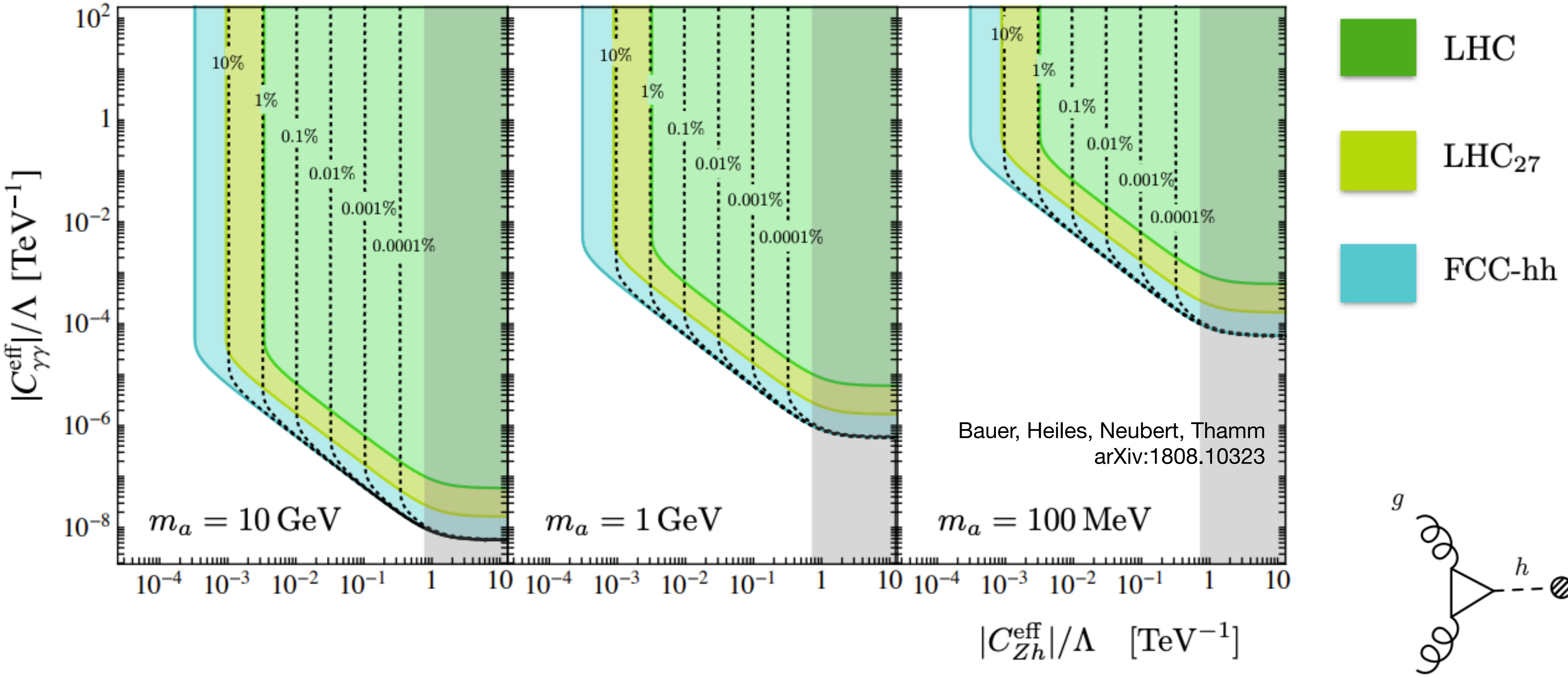
- ALP production and decay governed by two unrelated Wilson coefficients
- Decreasing ALP mass implies increased lifetime, means decreased sensitivity
- Larger coverage for lower $\sqrt{s}$ because $\sigma \propto 1/s$
- Contours for 4 events, dotted lines: variation of $BR(a \to \gamma\gamma)$ at FCC-ee

# Axion/ALPs portal: FCC-hh

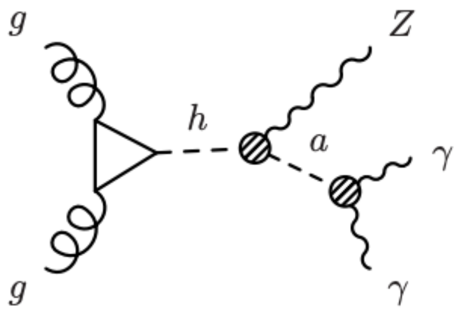


- At best comparable sensitivity for ALP - photon couplings as FCC-ee has larger luminosity and runs on the Z pole
- FCC-ee may even have higher precision

# Axion/ALPs portal: FCC-hh



Bauer, Heiles, Neubert, Thamm
arXiv:1808.10323



- Large gain in production cross section, large sensitivity to couplings
- At FCC-hh the Higgs mode is more promising than the Z mode

# Right handed neutrinos

## Type - I seesaw

$$\mathcal{M}_\nu = \begin{pmatrix} \mathbf{0} & M_D \\ M_D^{\mathsf{T}} & M_N \end{pmatrix}$$

Dirac mass, usually small $Y_\nu$

Majorana mass, can be heavy, can have $Y_N \sim 1$, introduces Lepton number violation

$$\mathcal{L} \supset Y^{\nu}_{ij} \overline{N}_i \; L_j \cdot H - \frac{1}{2} M_{ij} \overline{N}_i \; N_j^c$$

## Minimal inverse seesaw

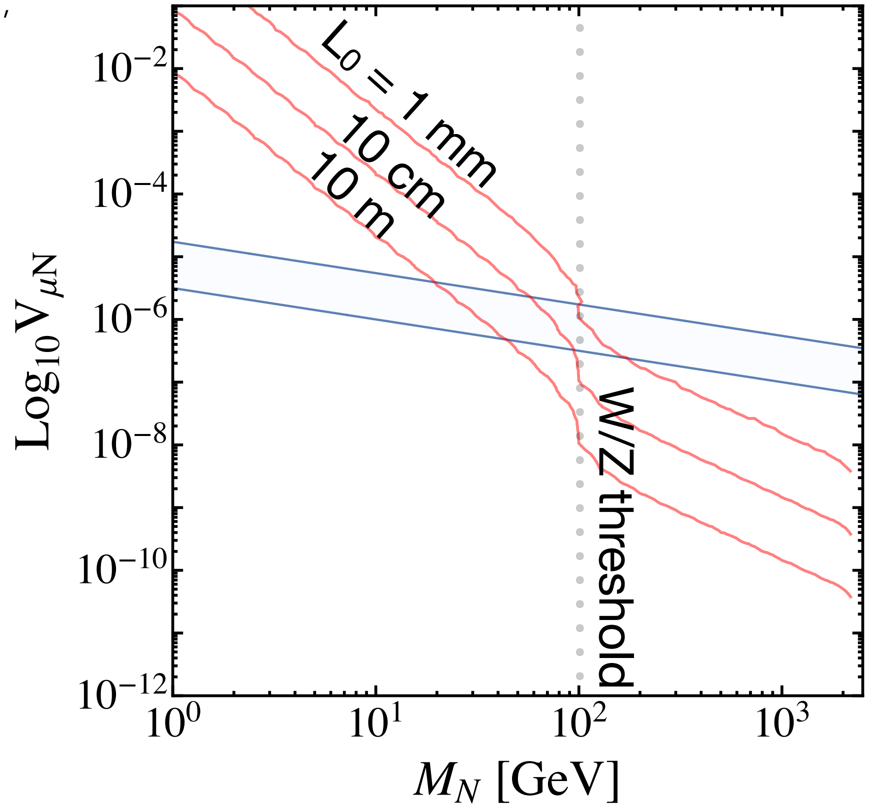
$$\mathcal{M}_\nu = \begin{pmatrix} 0 & m_D & 0 \\ m_D & 0 & m_S \\ 0 & m_S & \mu_S \end{pmatrix}$$

$$m_\nu \approx -\mu_S \frac{m_D^2}{m_S^2}$$

Also possible to generate neutrino masses with e.g. inverse seesaw

$$m_\nu \approx \frac{M_D^2}{M_N} = |V_{\mu N}|^2 \times m_N \qquad c\tau_N \propto \left(\frac{10^{-6}}{V_{lN}}\right)^2 \times \left(\frac{100\mathrm{GeV}}{M_N}\right)^5$$

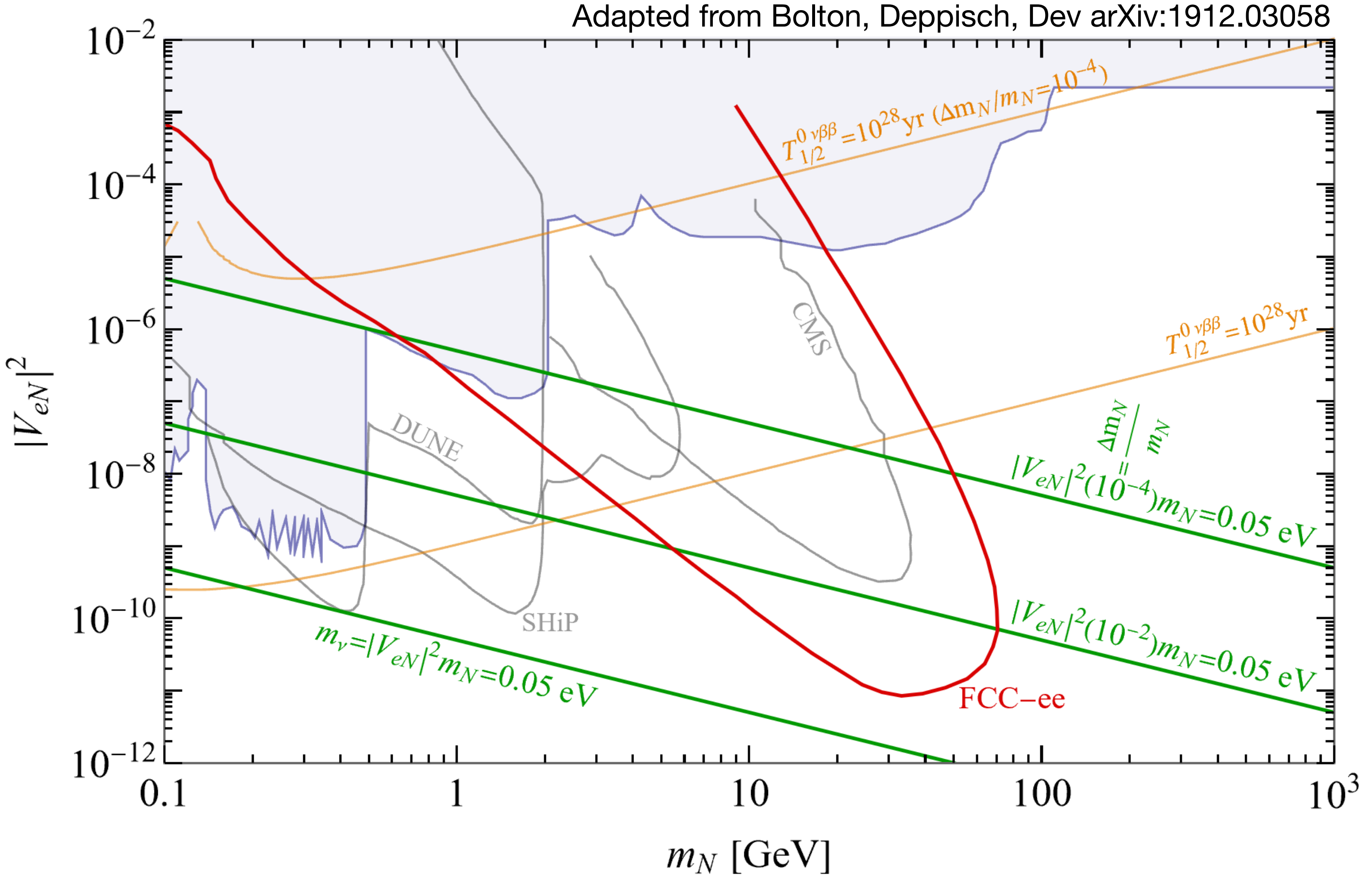
See e.g. Deppisch, New J. Phys. 17 (2015) 075019

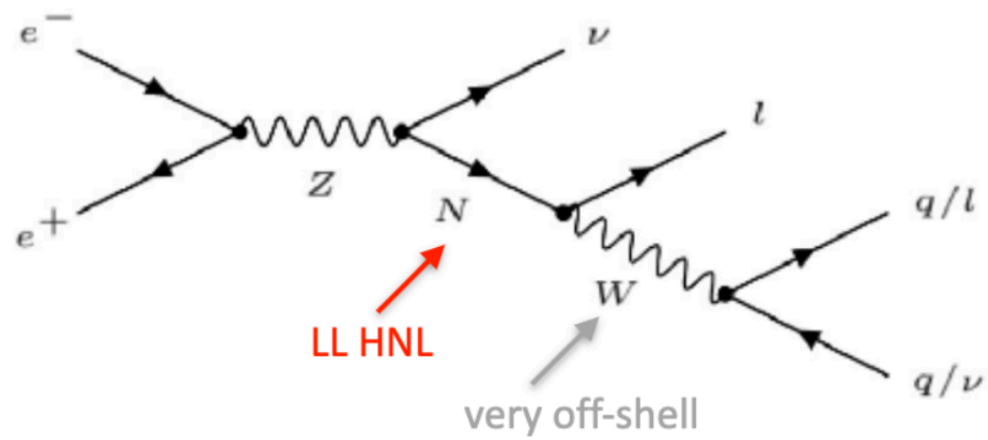


- Are SM neutrinos Dirac or Majorana?
- Are right handed neutrinos responsible for generating SM neutrino masses?
- Are there extra gauge/Higgs bosons featuring in right handed neutrino phenomenology?

# Sterile neutrinos

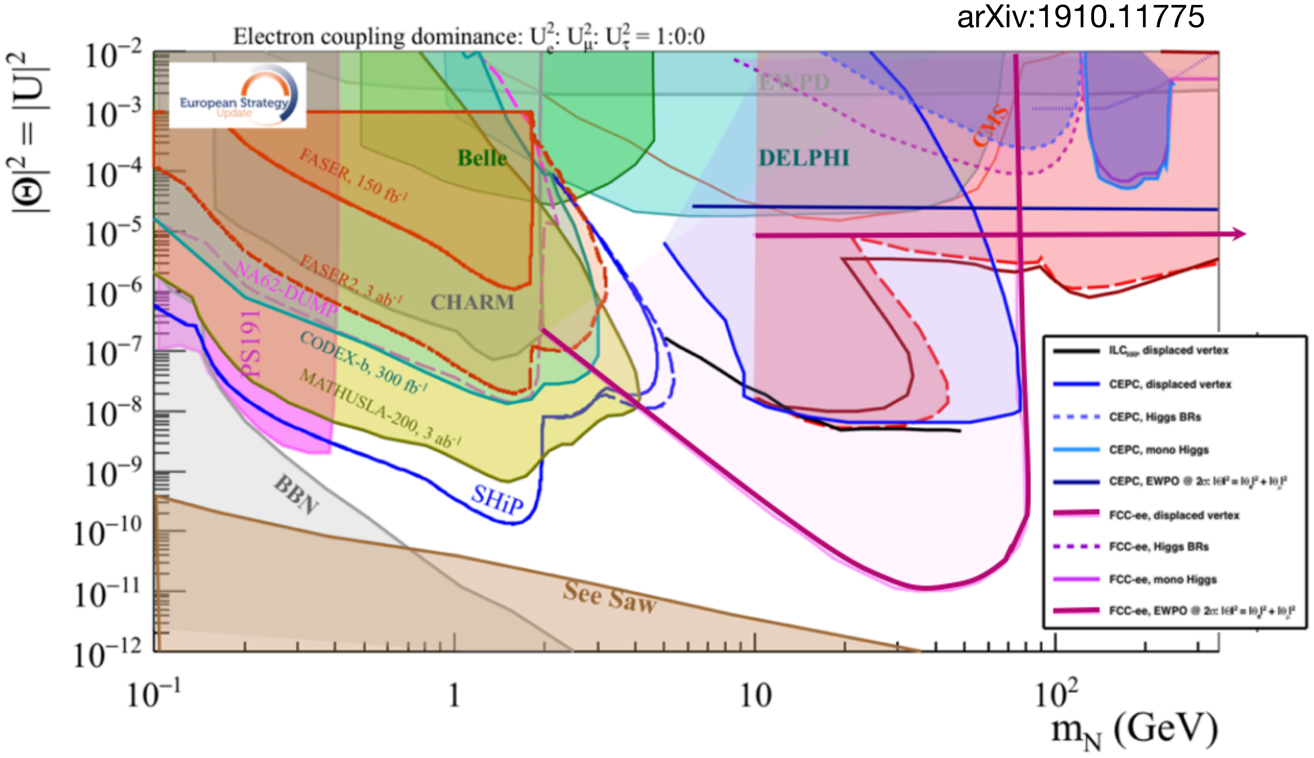
Adapted from Bolton, Deppisch, Dev arXiv:1912.03058



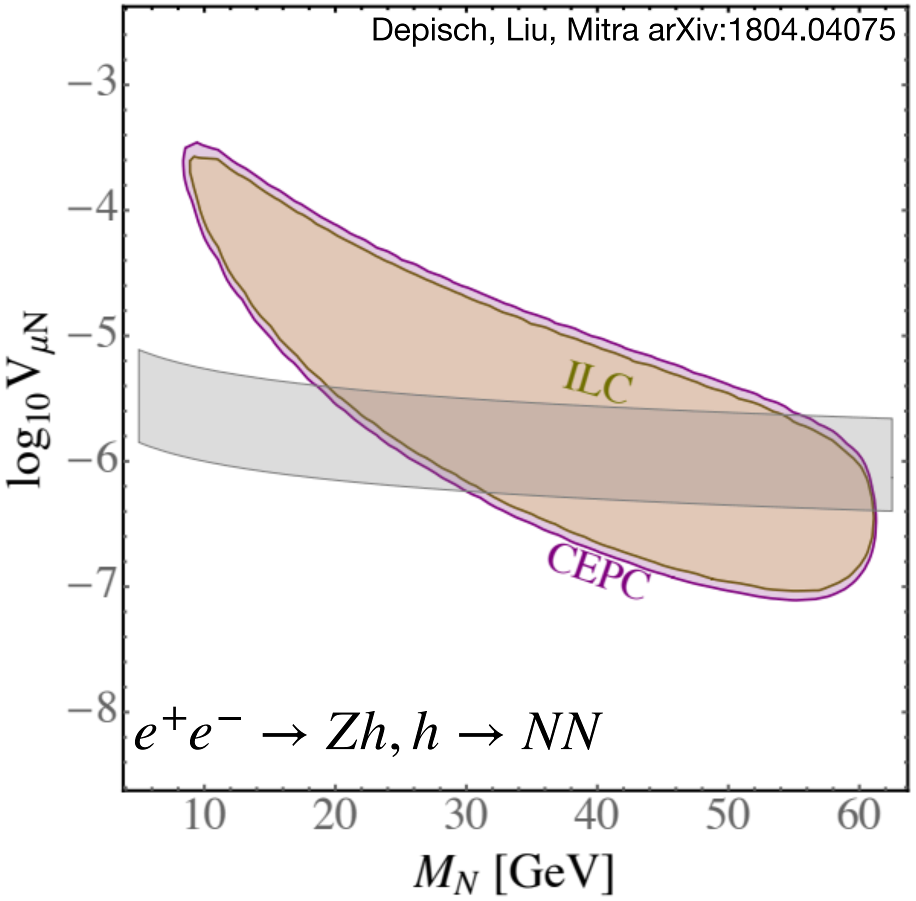


- Simplest production mechanism and assumption one sterile neutrino
- Complementarity with $0\nu\beta\beta$, possibility to investigate beyond type-I seesaw mechanisms
- Realistically, more than one right handed neutrinos will be present, necessity to consider beyond 1 flavour scenarios

arXiv:1910.11775



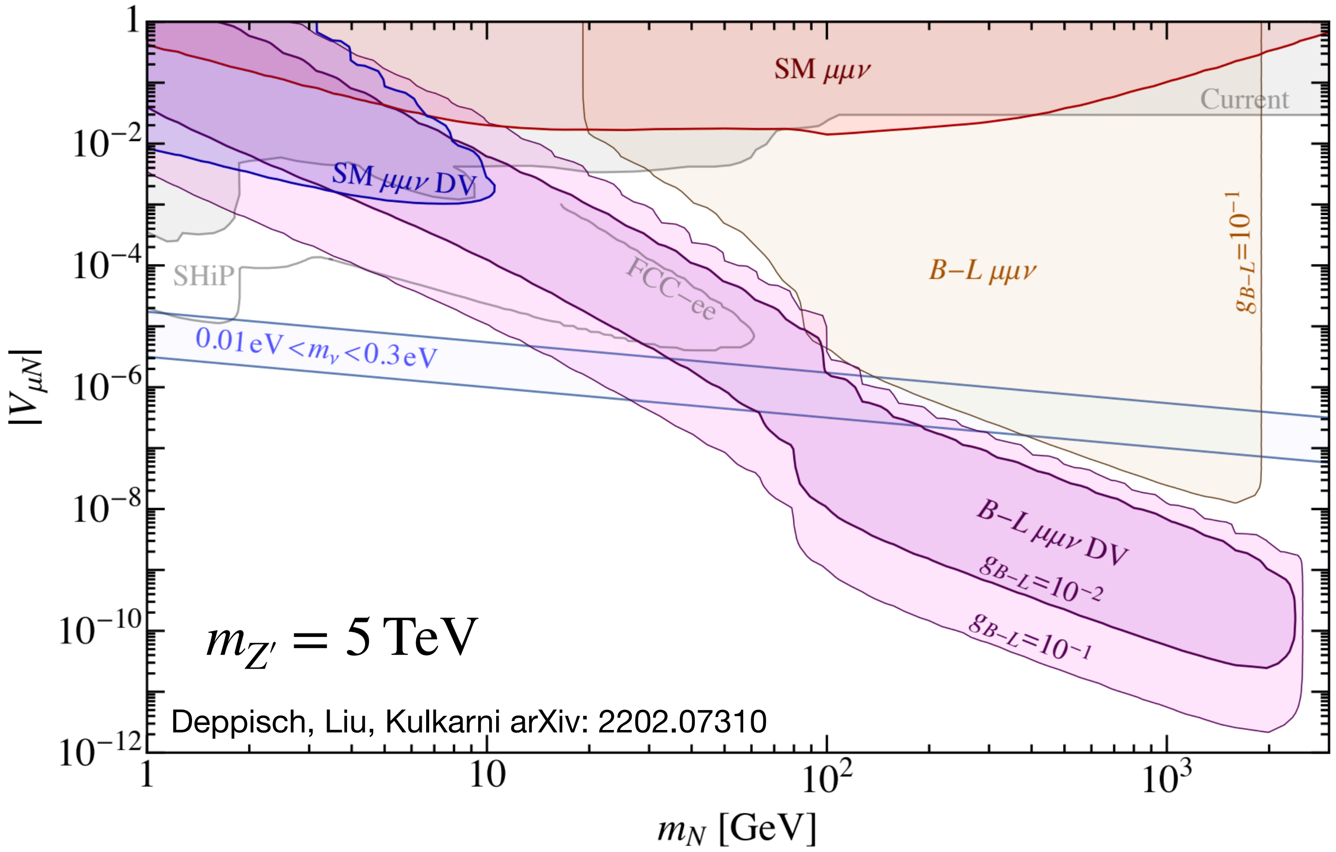
# RH in extended gauge sectors



Depisch, Liu, Mitra arXiv:1804.04075

- Heavy neutrinos can also be accommodated via SM gauge extensions, here an example of B-L extension
- Leads to additional operators for SM mediators to RH neutrino decays
- No prompt leptons in the final state, different event topology
- Possibility to learn about B-L breaking scale

- Huge complementarity between FCC-ee and FCC-hh
- Access to heavier (model specific) gauge bosons at FCC-hh
- HNL production with large boost at FCC-hh, large coverage of parameter space at the cost of additional model dependence



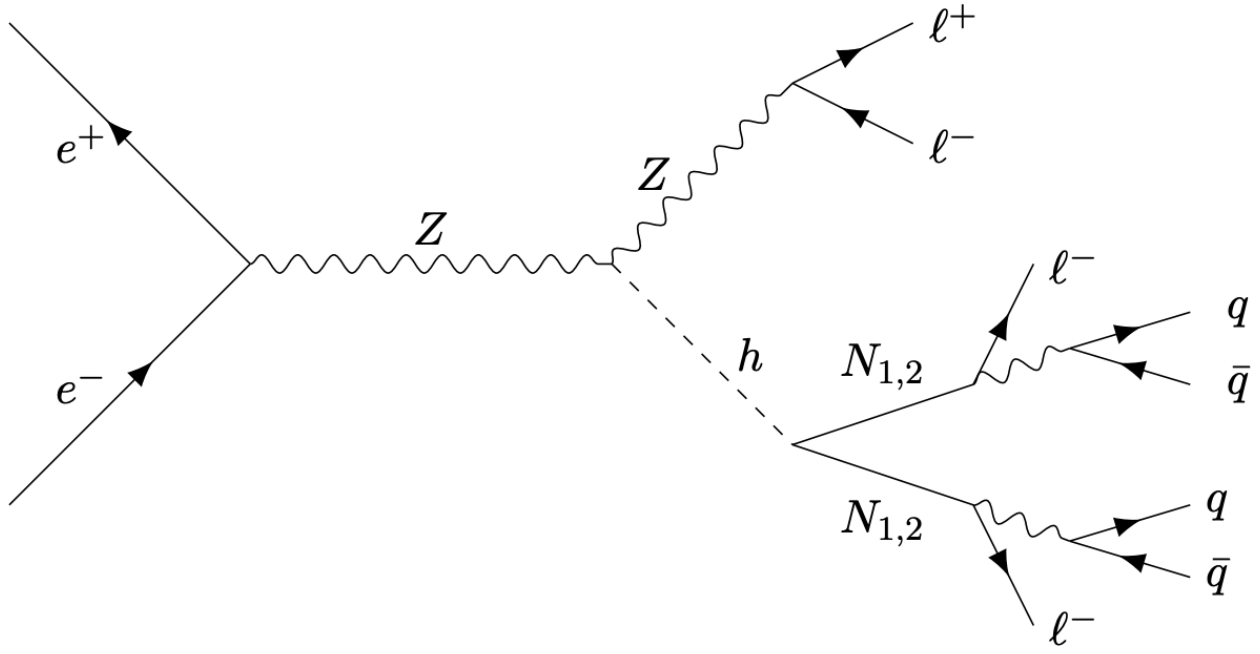
Deppisch, Liu, Kulkarni arXiv: 2202.07310

# RH neutrino via effective operators

Barducci, Bertuzzo, Caputo, Hernandez, Mele 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

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \bar{N} \not\partial N - \bar{L}_L Y_\nu \tilde{H} N - \frac{1}{2} M_N \bar{N}^c N + \sum_{n>4} \frac{\mathcal{O}^n}{\Lambda^{n-4}} + h.c.$$

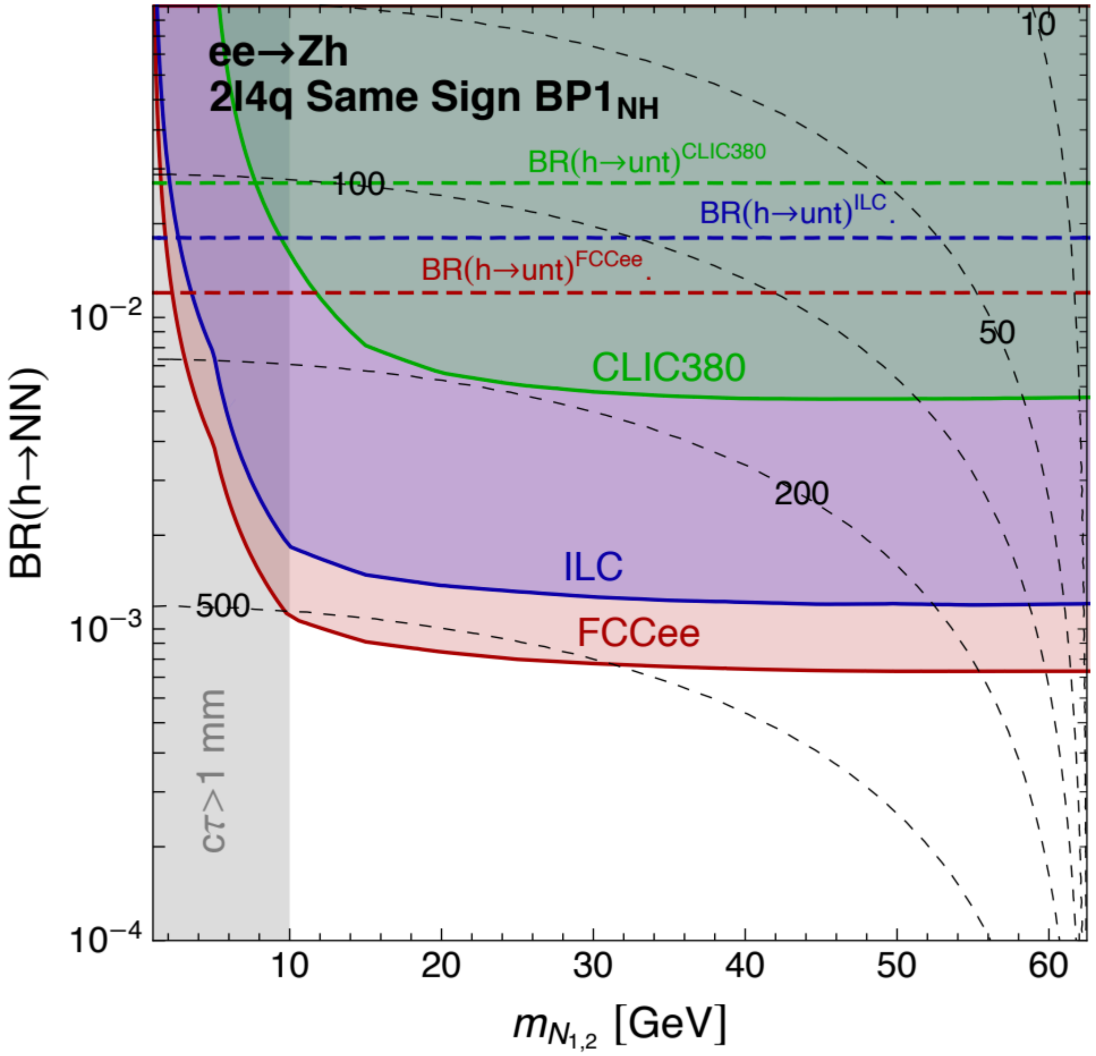


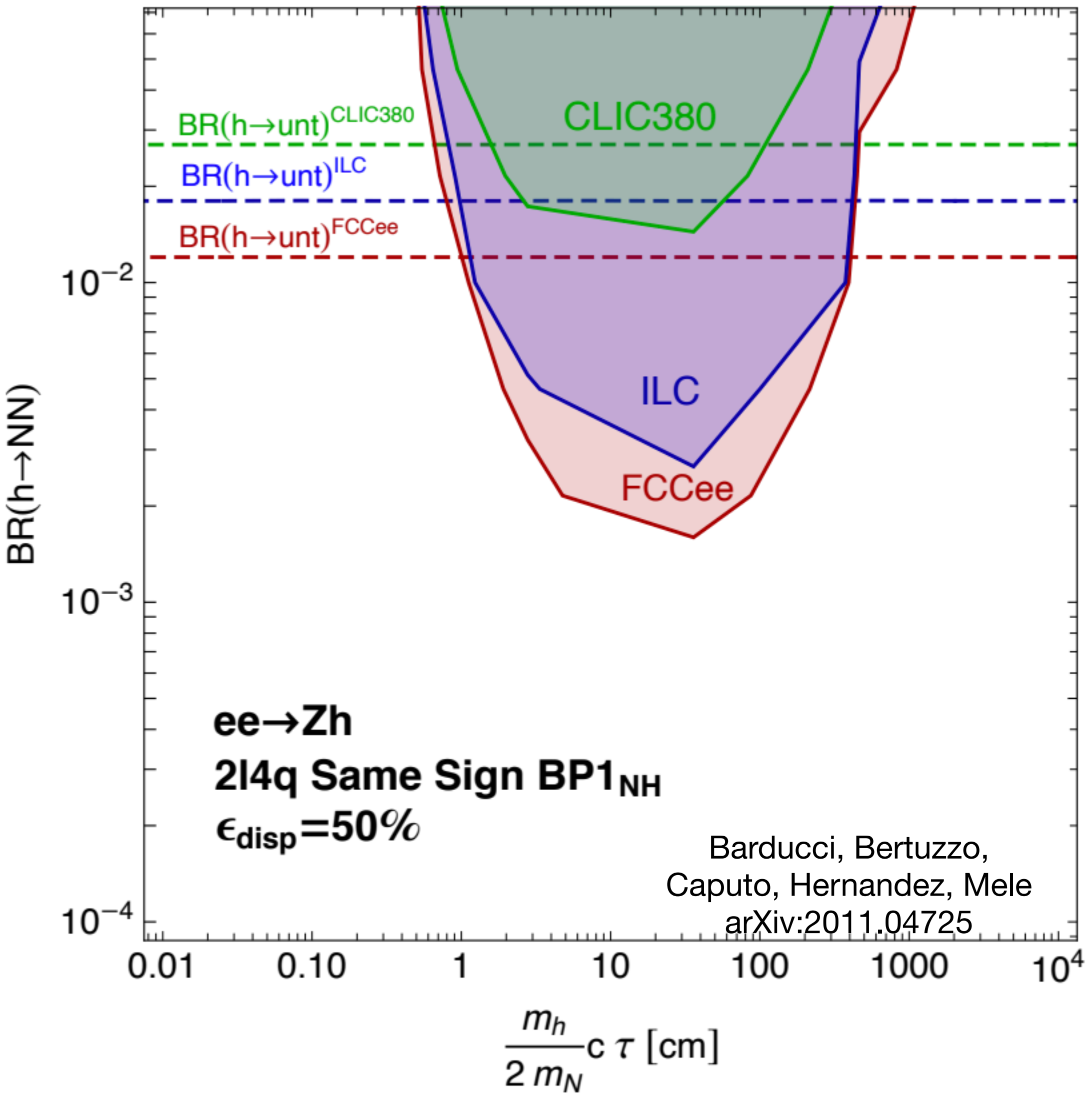
$$\begin{aligned}
\mathcal{O}_W &= \alpha_W (\bar{L}^c \tilde{H}^*)(\tilde{H}^\dagger L) \ , \\
\mathcal{O}_{NH} &= \alpha_{NH} (\bar{N}^c N)(H^\dagger H) \ , \\
\mathcal{O}_{NB} &= \alpha_{NB} \bar{N}^c \sigma^{\mu\nu} N B_{\mu\nu} \ ,
\end{aligned}$$

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

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

# Sensitivity estimates



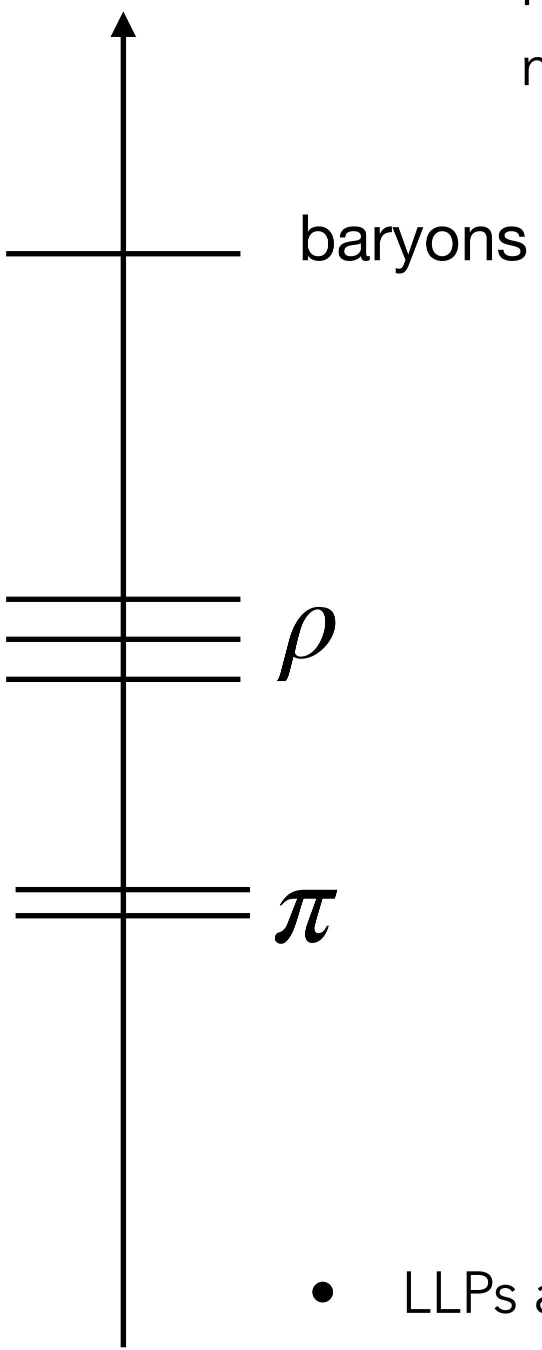


Barducci, Bertuzzo, Caputo, Hernandez, Mele arXiv:2011.04725

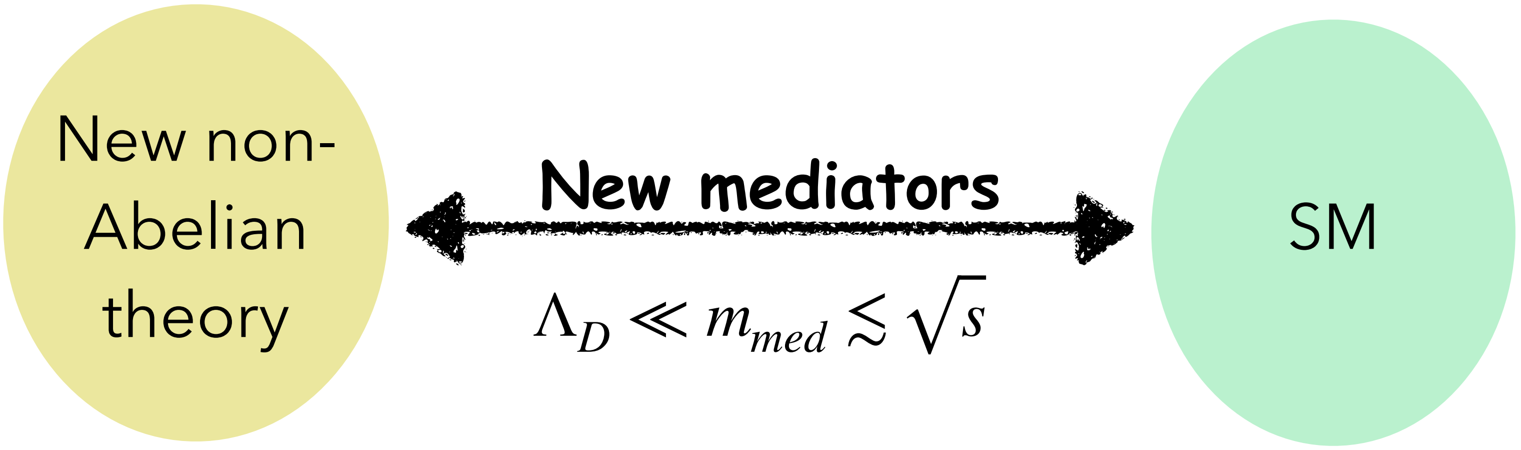
- Two benchmarks corresponding to different SM neutrino flavour mixing patterns
- Dashed lines correspond to the cutoff scale lambda
- Promising limits
- Favourable scenarios for cut-off scale above 500 GeV

# Dark matter

Spectrum

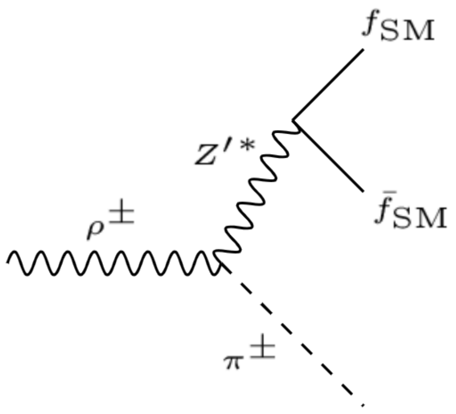


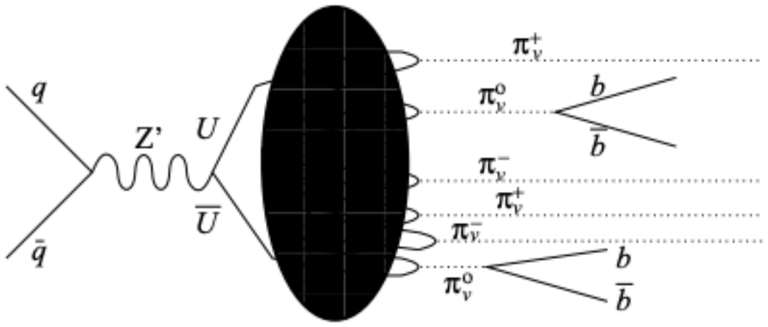
- Dark matter can result from confinement under new non-Abelian sector
- Resulting low energy (IR) spectrum can lead to pions or baryons as dark matter candidates depending on the details



$\Lambda_D \ll m_{med} \lesssim \sqrt{s}$

hep-ph/0604261;
arXiv:1503.00009;
arXiv:1502.05409;
arXiv:1903.04497;
arXiv:2203.09503
For fcc specific study see:
arXiv:2005.05221,
arXiv:1501.05310

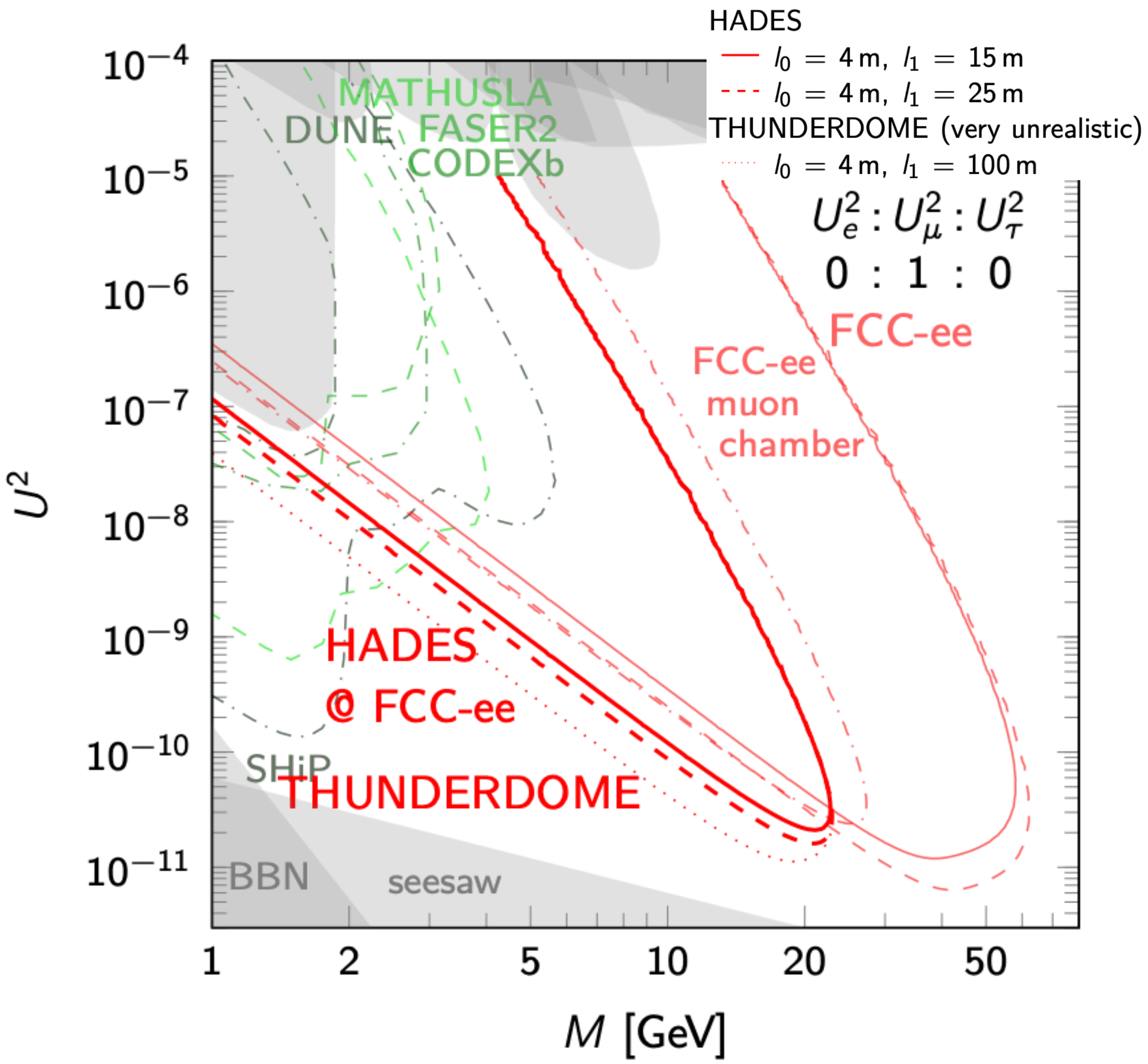


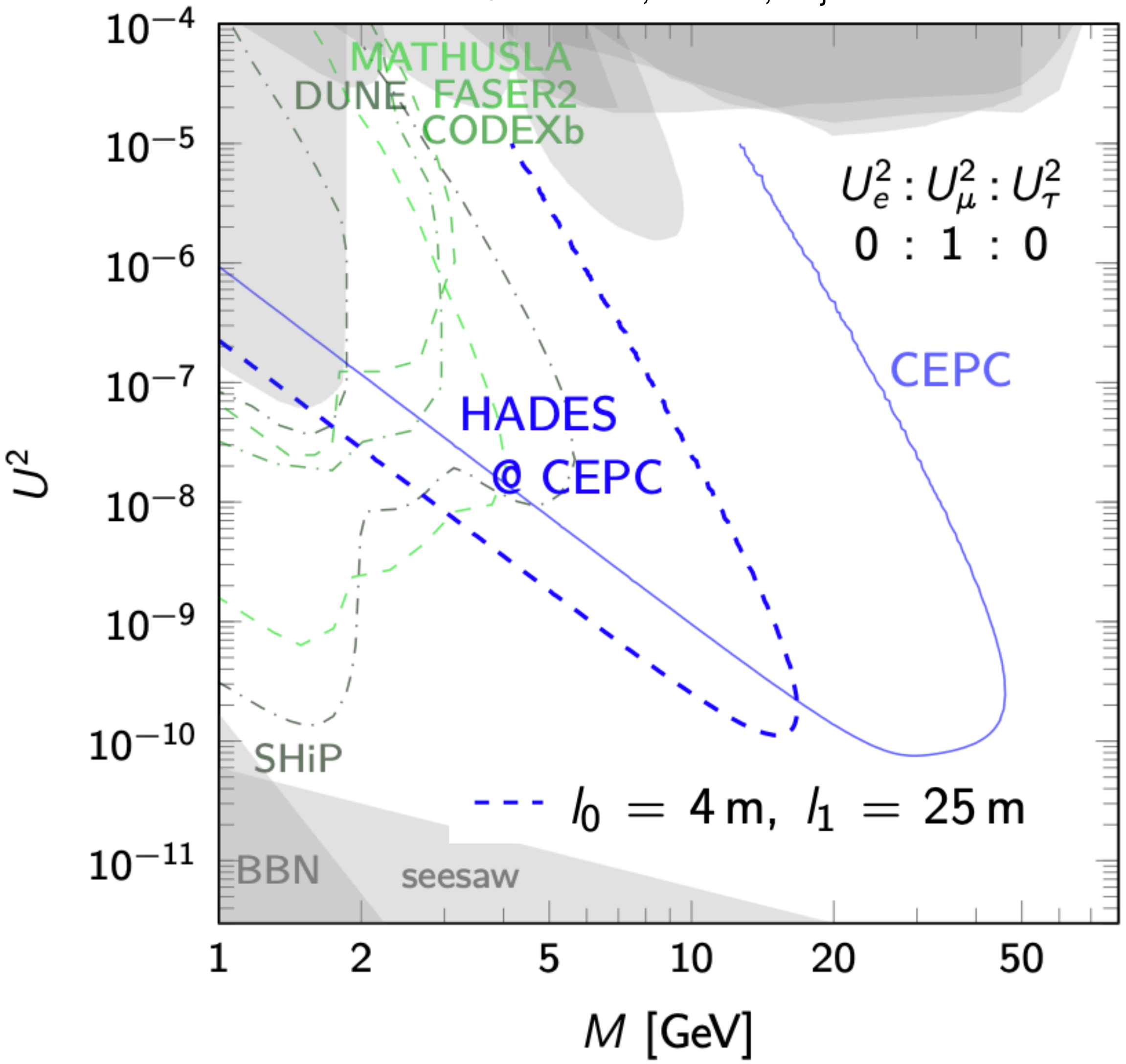


$\Gamma \propto \frac{1}{m_{Z'}^4}$ or worse

- LLPs arise generically and easily, ‘hide’ in SM jets, how to best look for them at FCC-ee and hh?

# Beyond ‘traditional’ detectors: FCC-ee



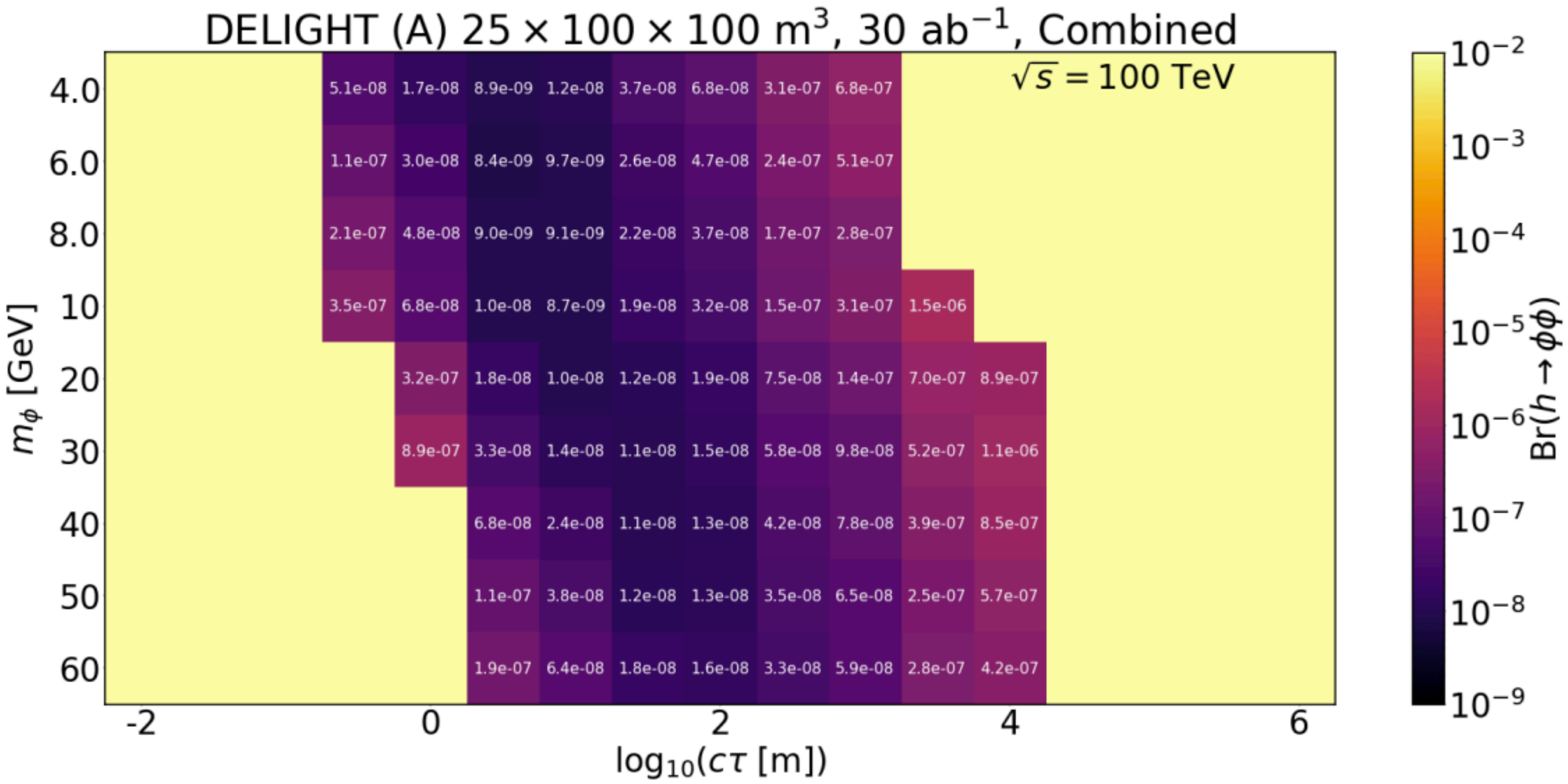


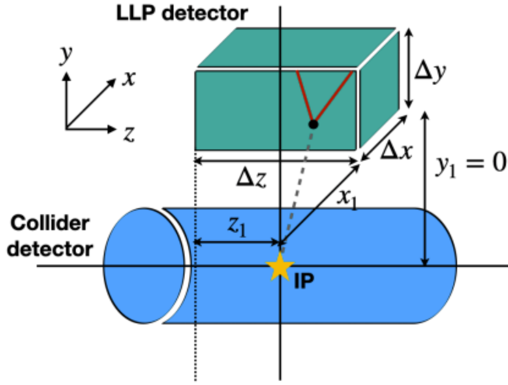
Charzaszcz, Drewes, Hajer arXiv:2011.01005

- 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
- Unique opportunity for $4\pi$ solid angle coverage
- Can help improve reach of LLPs, here case study of HNL

# Beyond ‘traditional’ detectors: FCC-hh

Bhattacherjee, Matsumoto, Sengupta arXiv:2111.02437





$x = 25$ m; $\eta = 0$

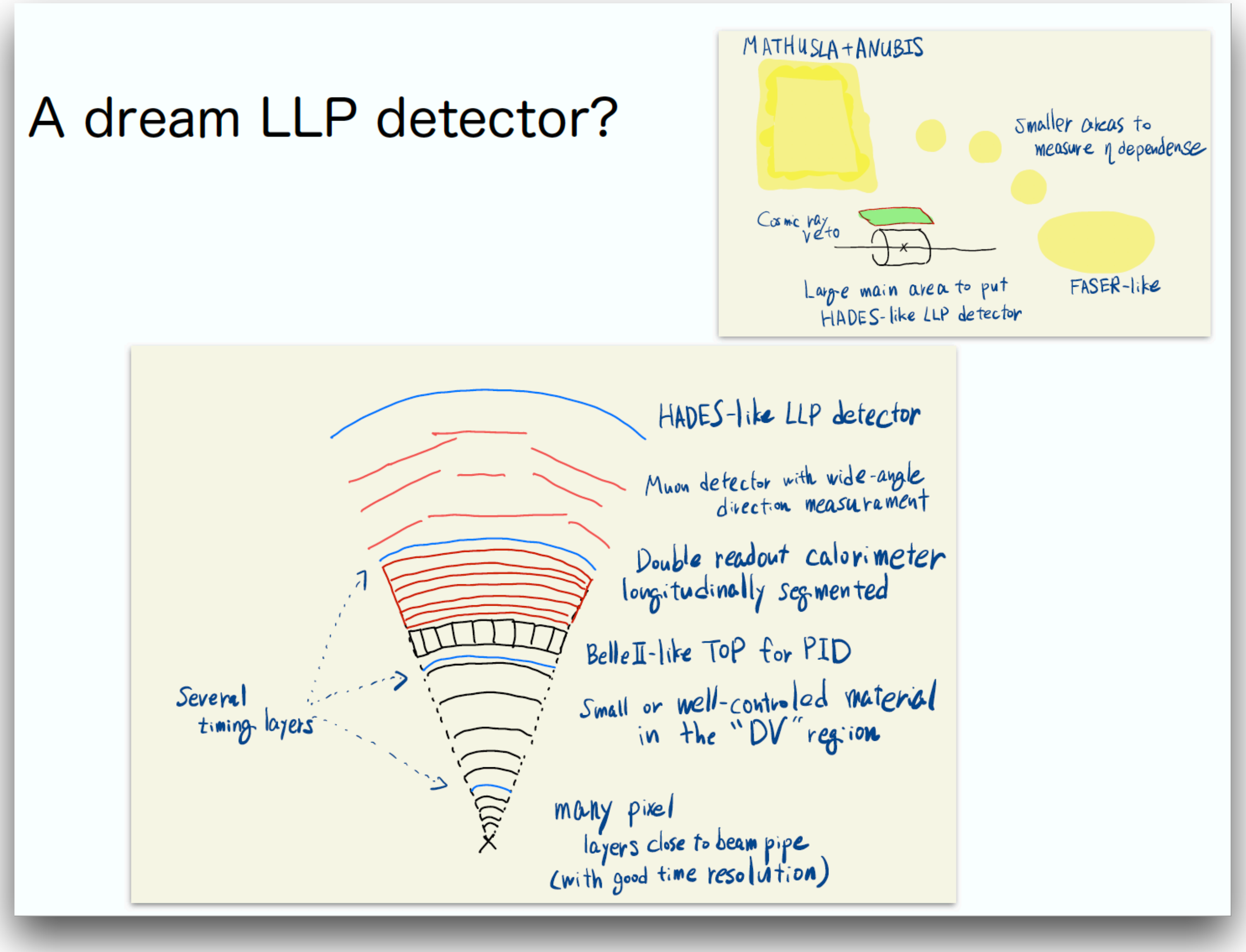
See also
Boyarsky, Mikulenko,
Ovchynnikov, Shchutska
arXiv:2204.01622

- Detector for long-lived particles at high energy of 100 TeV
- Same dimensions as MATHUSLA ($25 \times 100 \times 100\,\mathrm{m}^3$ ); transverse detector
- Has ca 500 times more sensitivity; 150 due to increased cross section and luminosity and factor 3-4 due to moving detector closer to IP

# Reality check

- All the studies I showed so far are somehow apples to oranges comparison
- Not all contours are done on same footing, not all studies done with realistic setup
- Good enough to get first estimate, but we need to have realistic expectations
- Can we do better?

See talk by M. McCullough



A dream LLP detector?

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)

See talk by Juliette Alimena

# Conclusions

- We want to make the best use of the available experimental data to learn about fundamental laws governing the Universe
- Searching for LLPs is one way of chasing that quest
- LLPs arise in a variety of BSM scenarios in solutions of problems from nature of dark matter to the Higgs hierarchy problem
- LLPs lead to a variety of final states, and demand new analysis techniques and probably improved/additional detectors
- FCC-ee and hh offer complementary information and are capable for delivering a more detailed understanding of new physics via LLP
- Similar considerations should also be given for FCC-eh physics (not covered in the talk)
- Most of the studies so far are done under simplistic assumptions, more realistic detector simulations are necessary for setting up our expectations

Thanks for the discussions A. Thamm, R. Gonzalez-Suarez, J. Alimena, M. Drewes, F. F. Deppisch, R. Sengupta