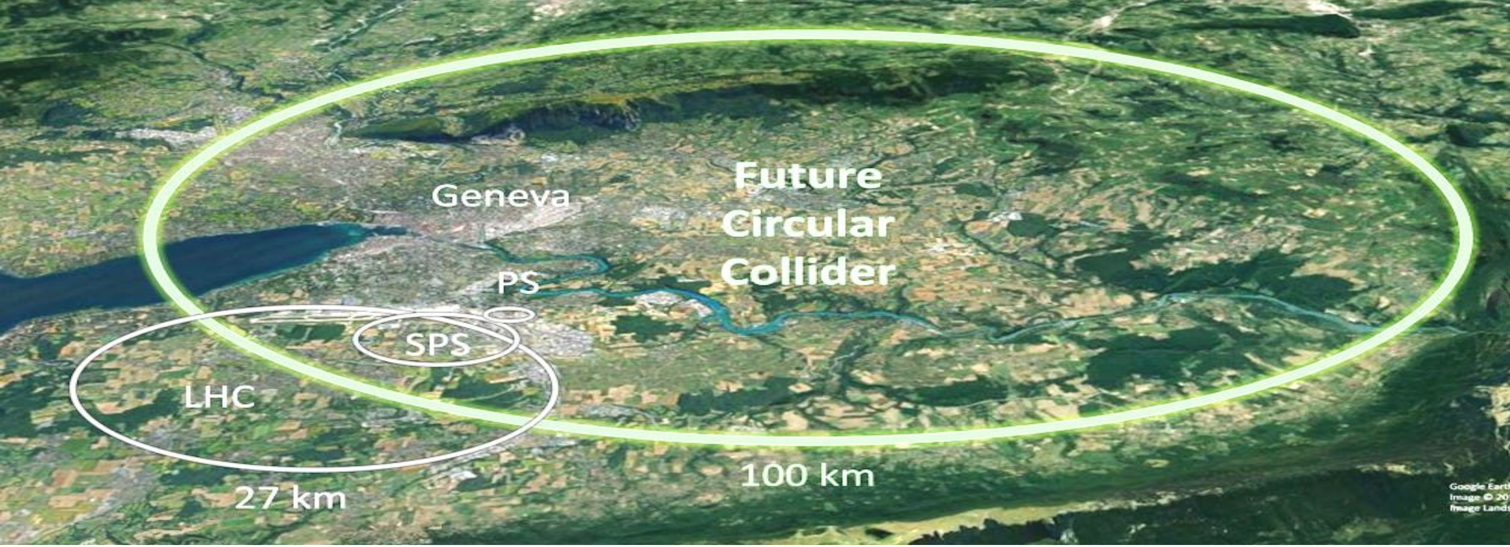

BSM Searches at the Lifetime Frontier at the FCCee

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Rheinische Friedrich-Wilhelms-Universität Bonn

Rundgespräch: Theory Hub for FCCee Physics
July 2-3, 2026

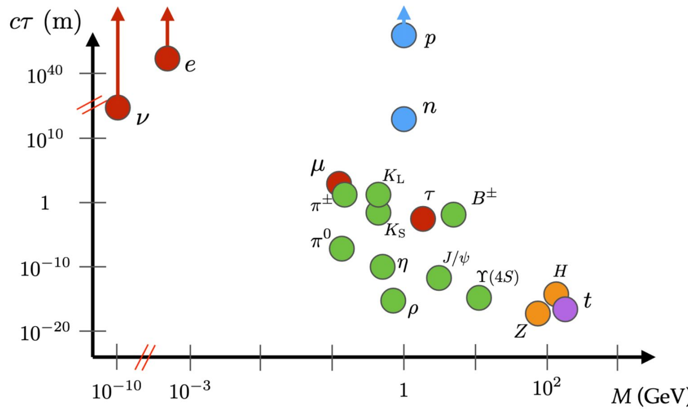
UNIVERSITÄT BONN

Motivation and Preliminary Work

Why Long-Lived Particles?

We have good reasons to think that there is new physics beyond the SM (dark matter, hierarchy problem, inflation, neutrino masses, baryogenesis ...)

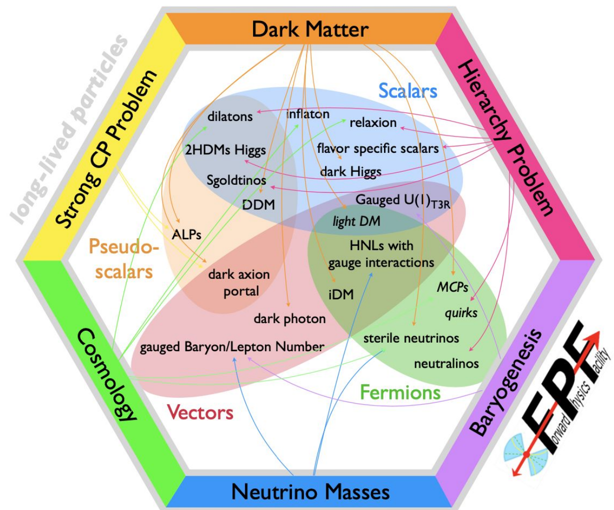
No evidence for new particles with conventional search strategies. Maybe we have been looking in the wrong place.



SM as inspiration:
many particles are long-lived

↓

search for new long-lived particles (LLPs) as sign of BSM physics



LLPs Prospects at the FCC

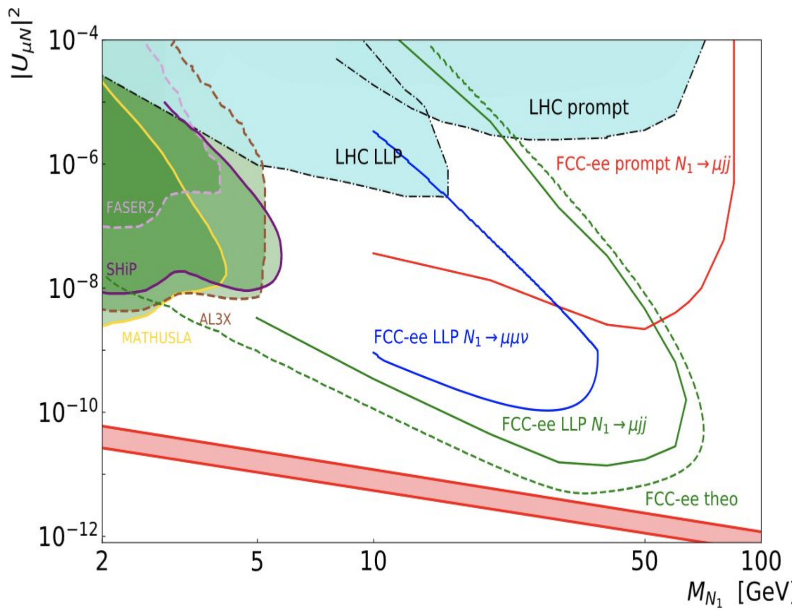
A variety of studies have shown great discovery potential of the FCCee for LLPs, exceeding existing/expected constraints by many orders of magnitude.

Example 1: Heavy Neutral Leptons

- GeV-mass sterile neutrino N
- abundantly produced via Z-decay
- BR(Z>vN) ~ U^2
- cτ ~ $mW^4 / U^2 \, mN^5$ ~ 1m
  for mN ~ 10 GeV , U~10^{-5}

- almost reaches Seesaw target line

- by far most studied model

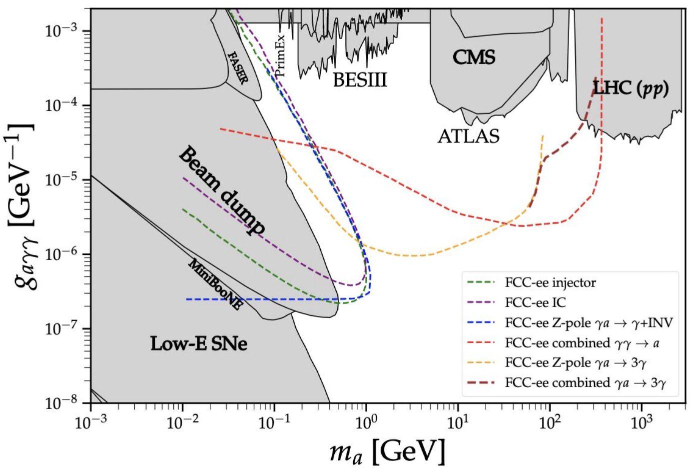


[FCC Feasibility Study, 2505.00272]

LLPs Prospects at the FCC

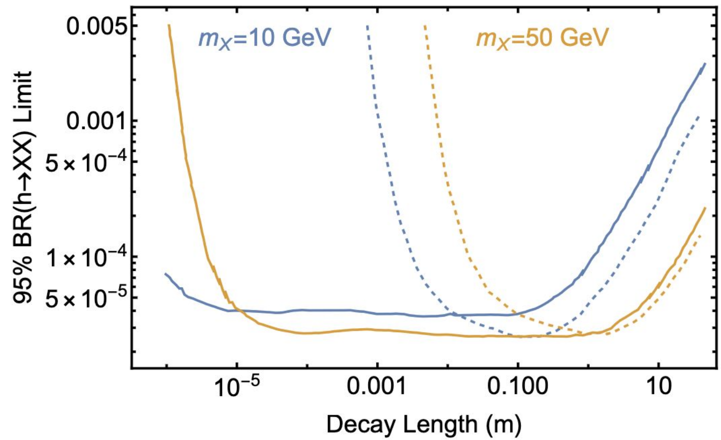
A variety of studies have shown great discovery potential of the FCCee for LLPs, exceeding existing/expected constraints by many orders of magnitude.

Example 2: Axion Like Particles



[Alimena et al, 2605.21452]

Example 3: Exotic Higgs Decays



[FCC Feasibility Study, 2505.00272]

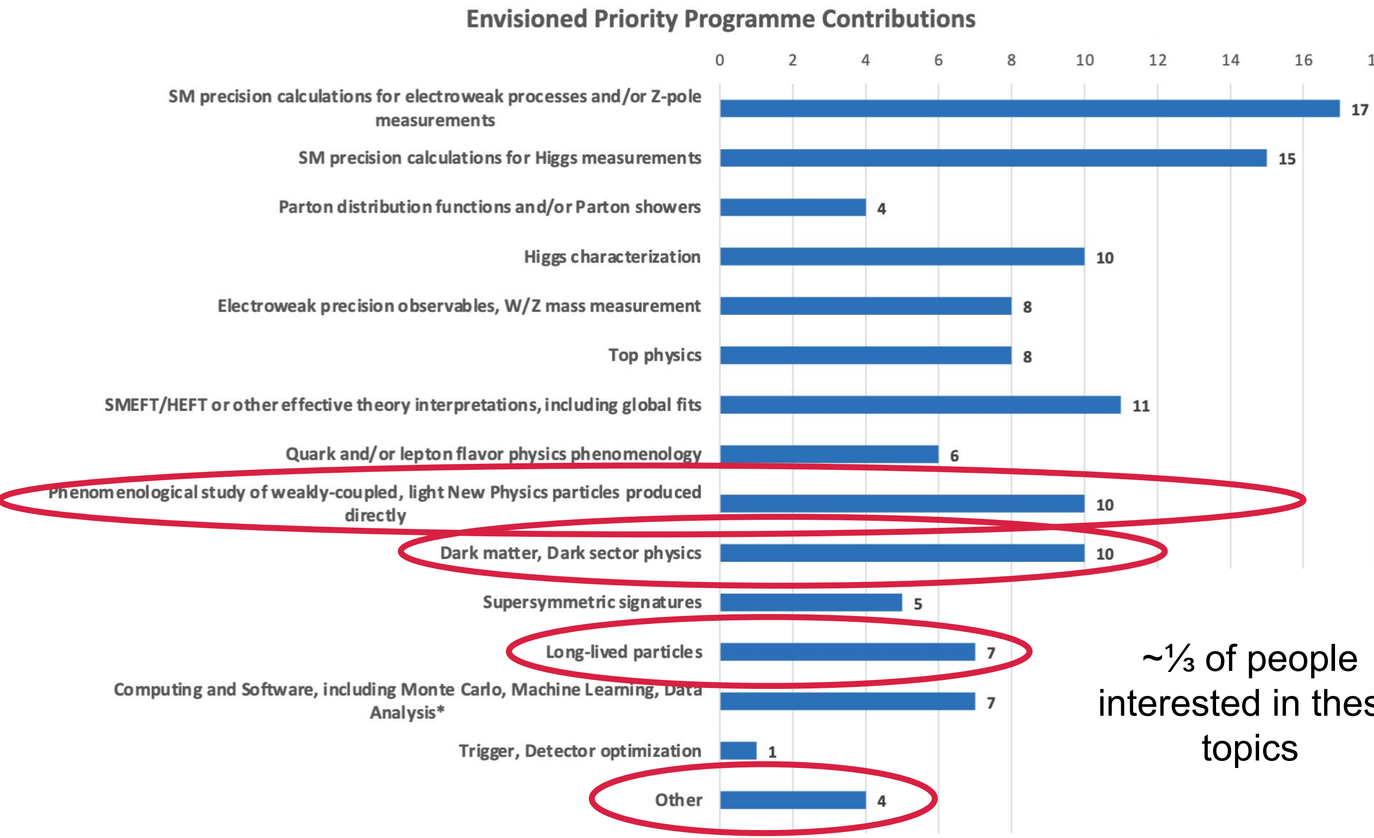
LLPs Prospects at the FCC

A variety of studies have shown great discovery potential of the FCCee for LLPs, exceeding existing/expected constraints by many orders of magnitude.

HNLs	Searching for type I seesaw mechanism in a two 3 Heavy Neutral Leptons scenario at FCC-ee	https://repository.cern/records/wyy8e-rp507
	Searches for Heavy Neutral Leptons at FCC-ee in final states including a muon	https://repository.cern/records/p006y-7dc15
	Sensitivity of the FCC-ee to decay of an HNL into a muon and two jets	https://repository.cern/records/9pc9x-kcn56
	Heavy Neutral Leptons Search in a Realistic Neutrino Oscillation Model at FCC-ee	https://repository.cern/records/rgehk-gqy70
	Updated studies on the sensitivity of FCC-ee to heavy neutral leptons coupling to electrons at the Z-pole run	https://repository.cern/records/fhwr2-1rp05
	Sensitivity of the FCC-ee to HNLs decaying to muon pairs and neutrinos	https://repository.cern/records/krn1s-h6w79
	Search for HNL at FCCee, and comparisons between Fast and Full Simulation	https://repository.cern/records/q0q05-6mj65
	Timing-based mass measurement of exotic long-lived particles at the FCC-ee	https://repository.cern/records/xq6hr-bqx92
ALPs	Sensitivity of the FCC-ee to axion-like particles at different center-of-mass energies	https://repository.cern/uploads/hbq84-09k23
	Sensitivity of the FCC-ee to decay of an axion-like-particle into two photons	https://repository.cern/records/bj20n-zty74
	Search for Axion-Like Particles decaying into a pair of gluons at FCC-ee	https://repository.cern/records/93ym3-tc924
Exotic Higgs	Long-Lived Particles from exotic Higgs decays at the FCC-ee	https://new-cds.cern.ch/records/xgyvv-xfd72
	Long-lived particles from exotic Higgs decays at the FCC-ee - detector comparison and additional Z decay modes	https://repository.cern/records/0b8zq-69b06
Dark photon	Sensitivity of the FCC-ee to the decay of a dark photon into a pair	https://repository.cern/records/g4q9q-gk718
SUSY	Charged long-lived particles in the GMSB scenario at the Future Circular Collider (FCC-ee)	https://repository.cern/records/2q6cj-yqe08
Z'	Leptophilic Z' bosons at the FCC-ee: a case study	https://repository.cern/records/ztx81-xmj10

[Gonzalez Suarez, FCC Week 26]

Overview and Interest



~⅓ of people interested in these topics

Open Questions

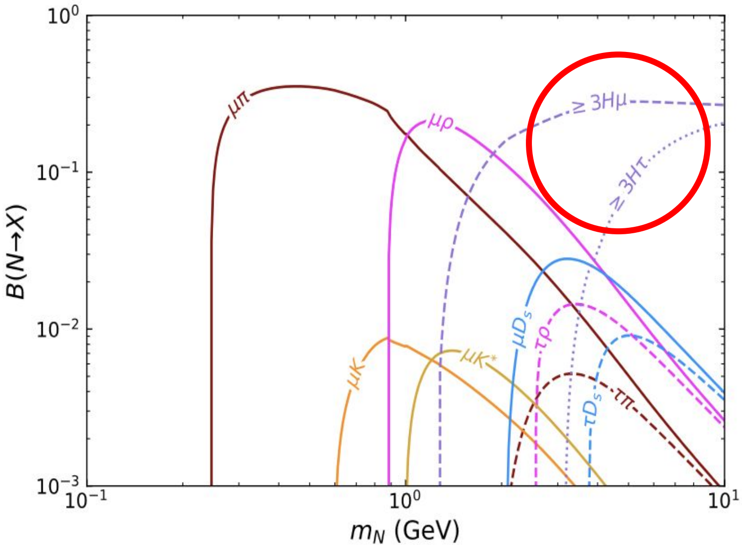
I was asked by the organizers to summarize open questions on the theory side that could be addressed through the Priority Programme.

Thanks also to Julietta Alimena, Felix Kahlhöfer, Joachim Kopp and Tilman Plehn for their input.

Properties of LLPs

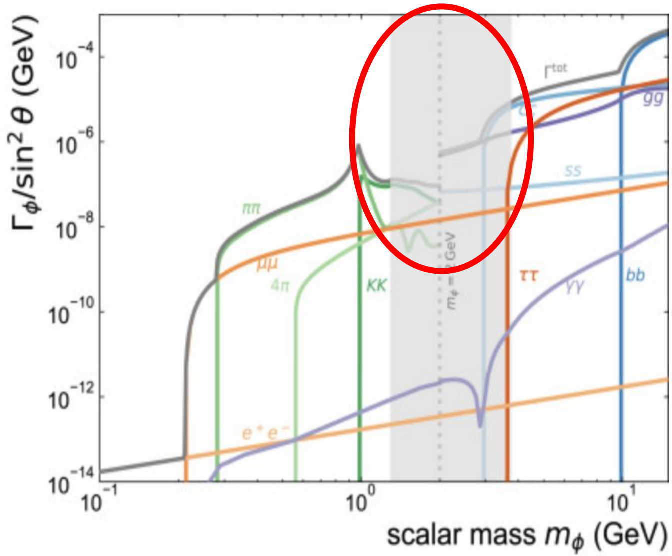
For many GeV scale LLPs, lifetime and BR are still partially known.
Theory uncertainties have not been quantified.

HNLs



[Feng et al, 2405.07330]

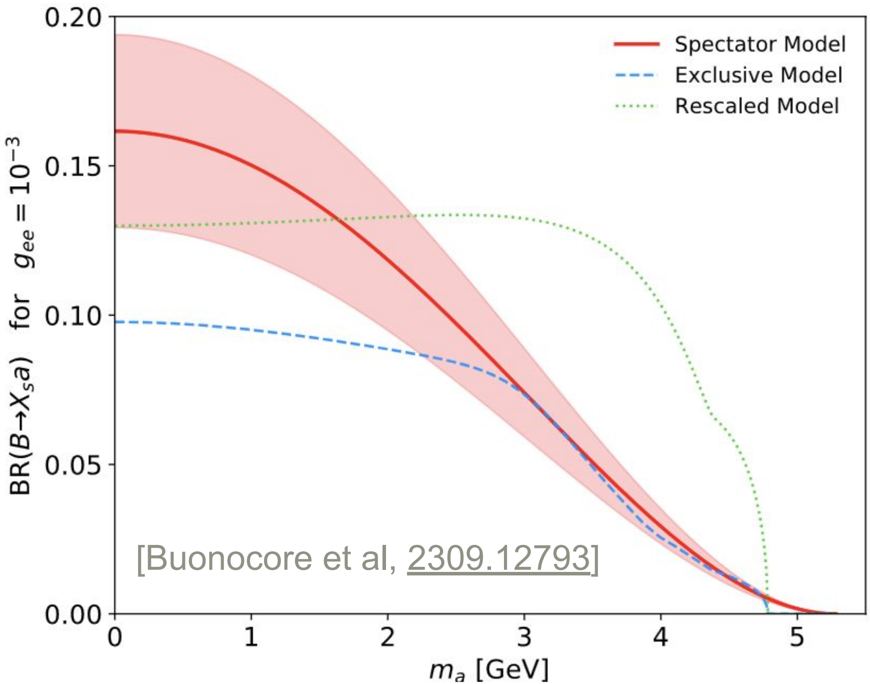
Dark Higgs



[Ferber et al, 2305.16169]

Production of LLPs

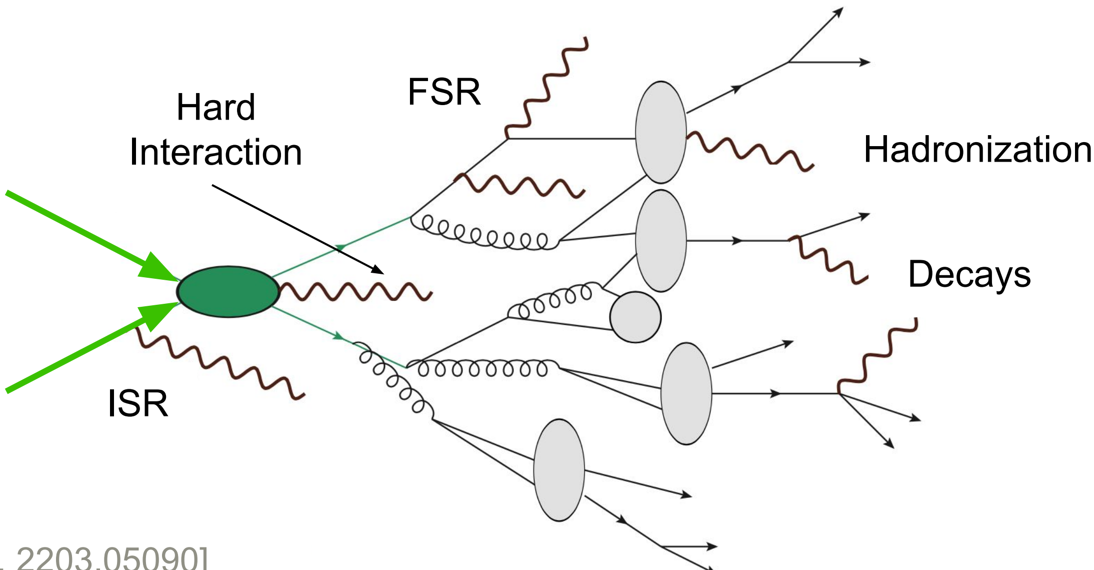
So far, most studies assume LLPs to be produced in primary collisions, Z/H decays or subsequent meson decays. Still sizable uncertainties.



Production of LLPs

So far, most studies assume LLPs to be produced in primary collisions, Z/H decays or subsequent meson decays. Still sizable uncertainties.

Other production mechanisms (e.g. in shower / hadronization) may contribute as significantly. Uncertainties and simulation tools needed. Only few studies so far.



[Feng et al, 2203.05090]

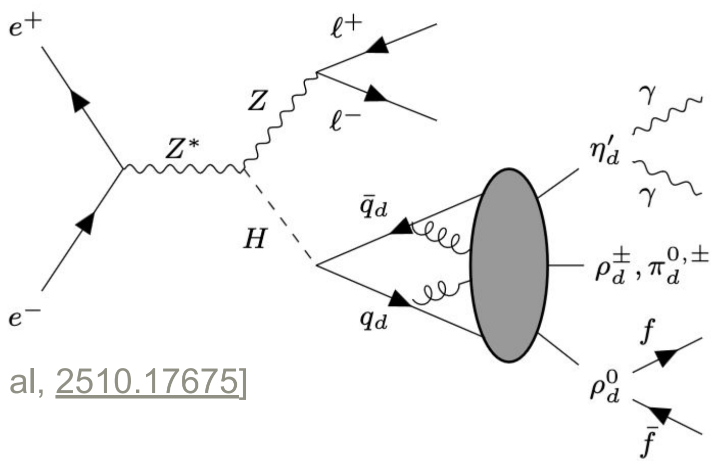
Dark Shower and LLPs

Discussions with Felix Kahlhöfer

In addition to SM showers, dark Sector particles can also be produced in dark showers. Expected in many confining hidden sector models.

Diverse phenomenology: dark showers and dark hadronization; dark hadrons and glueballs; prompt and displaced decays. Possible interplay between different portals (e.g Higgs and dark photon).

Better understanding of dark shower / hadronization with more realistic assumptions and reliable simulation tools needed.



[Kahlhofer et al, 2510.17675]

Tools

LLP Production / Decay often not implemented in standard generation tools, especially for light LLPs.

Typically dedicated simulation tools such as FORESEE (forward physics), ALPINIST (ALPs), MadDump/SensCalc (Beam dumps), … .

Various tools often use different modeling of production/lifetime/BR, leading to inconsistent results.

Fast detector response simulation (equivalent to Delphes) often not possible.

Recasting tools, including both for previous and anticipated FCC results (currently no LLPs in CheckMate and RIVET).

dedicated / better tools are needed

ML for LLPs

Discussions with Tilman Plehn and Gregor Kasieczka

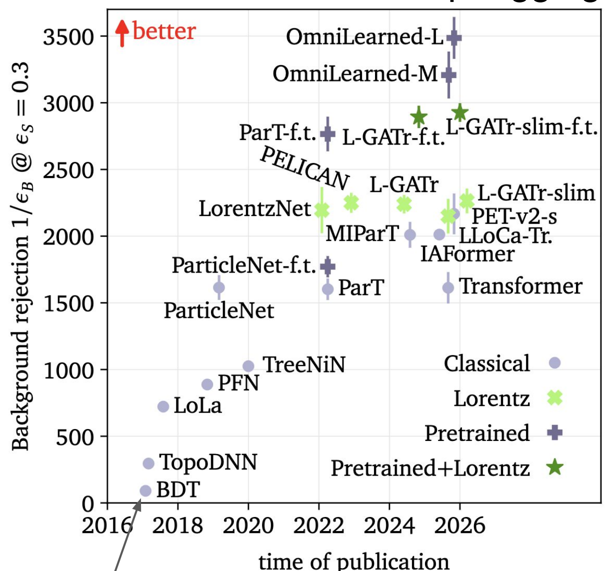
While some LLP signatures are easy to spot, others may be very subtle or subject to large backgrounds. Advances in ML will surely help.

ML taggers for B/D/τ ID and jet classification are the industry standard at the LHC.

These are prototypes for short-lived LLP ID at FCCee.

ML and LLPs so far comparably less explored

top tagging



[Petitjean et al 2512.17011]

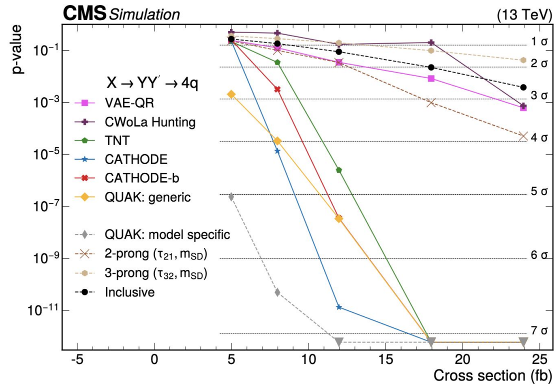
complexity of most FCC studies

ML for LLPs

Discussions with Tilman Plehn and Gregor Kasieczka

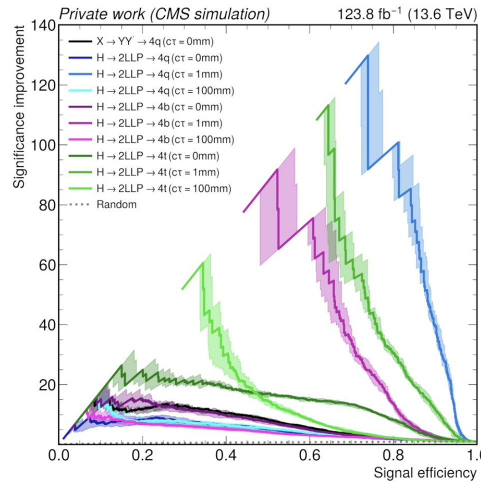
Anomaly detection significantly improves the sensitivity of searches already at LHC.

First studies suggest that same methods also work beautifully for LLPs.



German groups already leading world-wide efforts.

Projects, that need to be finances now to transfer knowledge from LHC to FCC.



provided by Gregor Kasieczka

ML can also help improving simulation tools.
[ML for Event Gen Whitepaper 2203.07460]

Models of LLPs

Discussions with Julitta Alimena

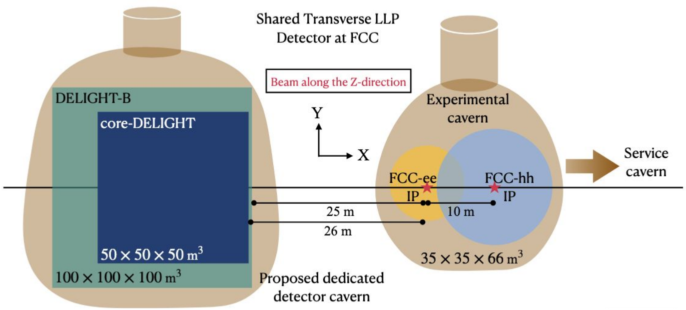
Various open items identified by FCC BSM WG
(from overview talk by R. Gonzalez Suarez)

What we want and what we are thinking of

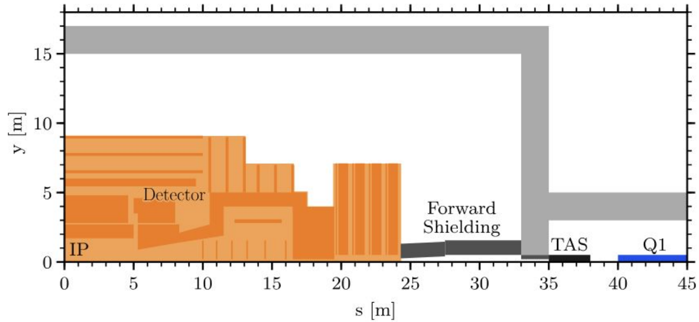
- **HNL model studies**
  - how to extract model parameters from signal?
- **ALP model files**
  - common stable UFO for ALP
  - python implementation of full NLO couplings
- **Unified studies of ALP searches**
  - Include all channels sensitive to C_{WW}, C_{BB} and C_{FF} couplings
  - includes VBF ALP production in ZZ and Zγ channels
- **ALPs from Higgs decays**
- **LLPs from SUSY**
  - Survey possible channels
  - adapt linear collider studies?
- **Scalars**
  - explore different decay channels for scalar portal

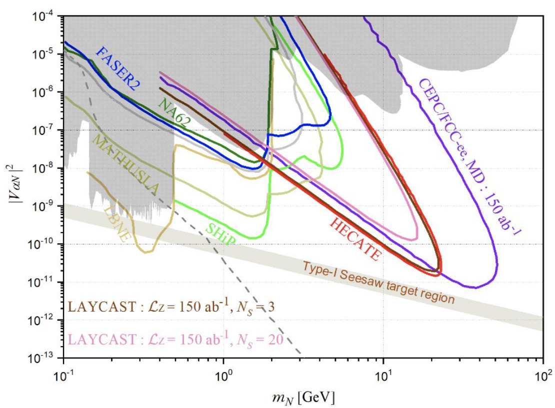
Auxiliary Detectors

DELIGHT:
MATHUSLA-like detector



HECATE and LAYCAST:
ANUBIS-like detector





Typically huge volumes requires to exceed sensitivity of main detectors.

Need for better motivations … .

Neutrinos at FCC

Discussions with Joachim Kopp

We produce few x 10^{12} Z bosons and hence ~10^{12} neutrinos of all 3 flavours.

Monochromatic neutrino beam with $E_\nu = m_Z/2$.

Interaction probability in calorimeter consisting of 1m of steel: $P = 10^{-10}$
→ we expect O(100) neutrinos in calorimeter.

Easy to see: appearing jet + missing energy

More event possible in other detector elements (muon system) or dedicated detector.

Possible physics potential:
- test flavor-universality in neutrino interactions and $Z \to \nu\nu$ decays
- constrain some SMEFT operators involving especially the third generation of leptons
- constrain scenario where the invisible Z width is not entirely due to neutrinos
- add a new data point to the plot of $\sin^2(\theta_w)$ vs. energy.
- constrain models with $Z \to \nu\nu$ decays, eg. Lmu-Lau.

Summary

LLPs have many physics motivations.

A variety of studies have shown great discovery potential of the FCCee for LLPs, exceeding existing/expected constraints by many orders of magnitude.

There are still large O(1) theory uncertainties (lifetime, BR, production rate). We may even still miss important production modes.

Better and more coherent tools are needed.

Main problem will be to identity LLPs: classification, anomaly detection, … . ML efforts still at beginning even at LHC.

Evolving field, expect new ideas/models/signatures/detectors in upcoming years.