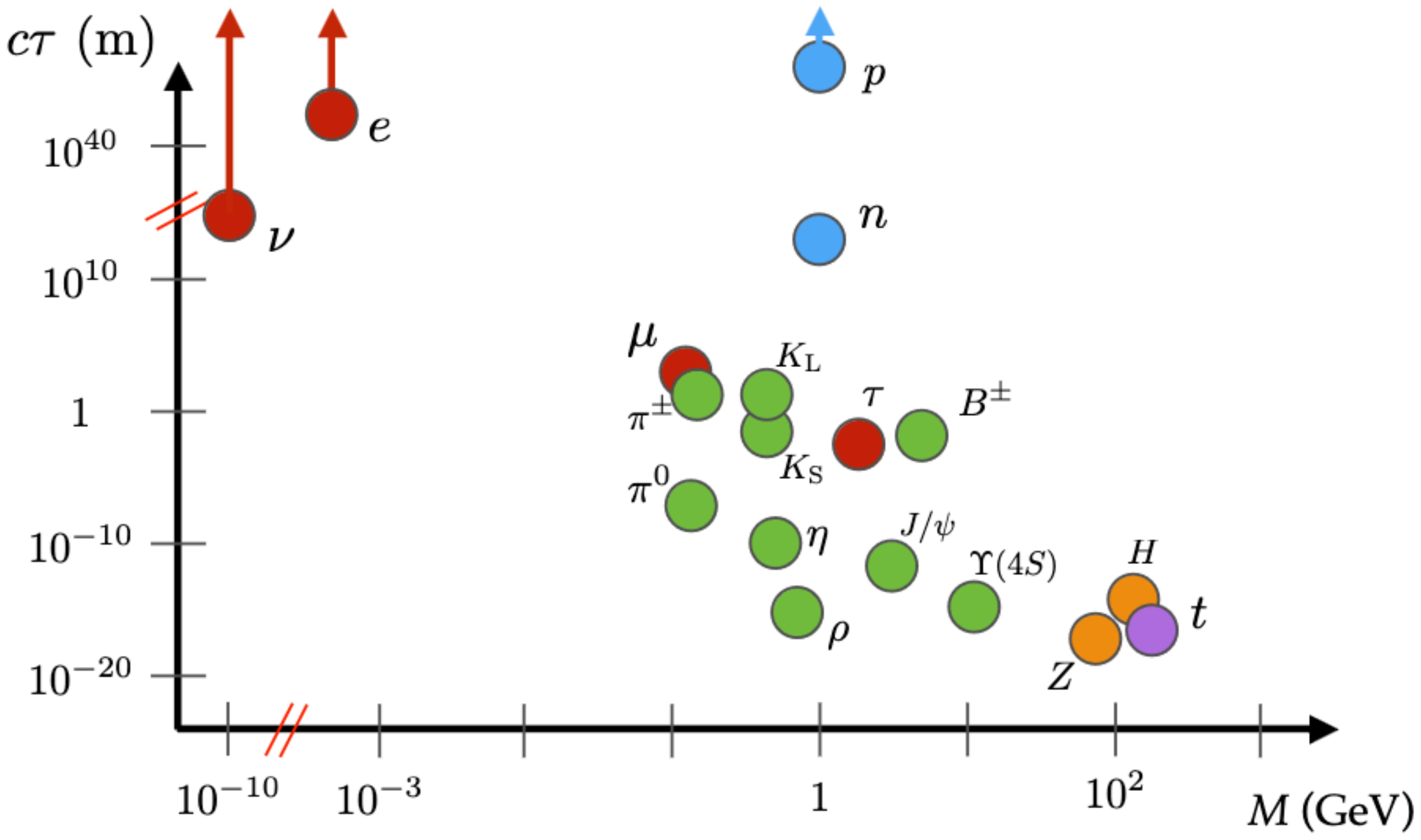
Long lived particles at colliders and beyond

Blois 2023: 34th Rencontres de Blois on "Particle Physics and Cosmology”
Château of Blois, 14-19 May 2023

Rebeca Gonzalez Suarez - Uppsala University

Long-lived particles

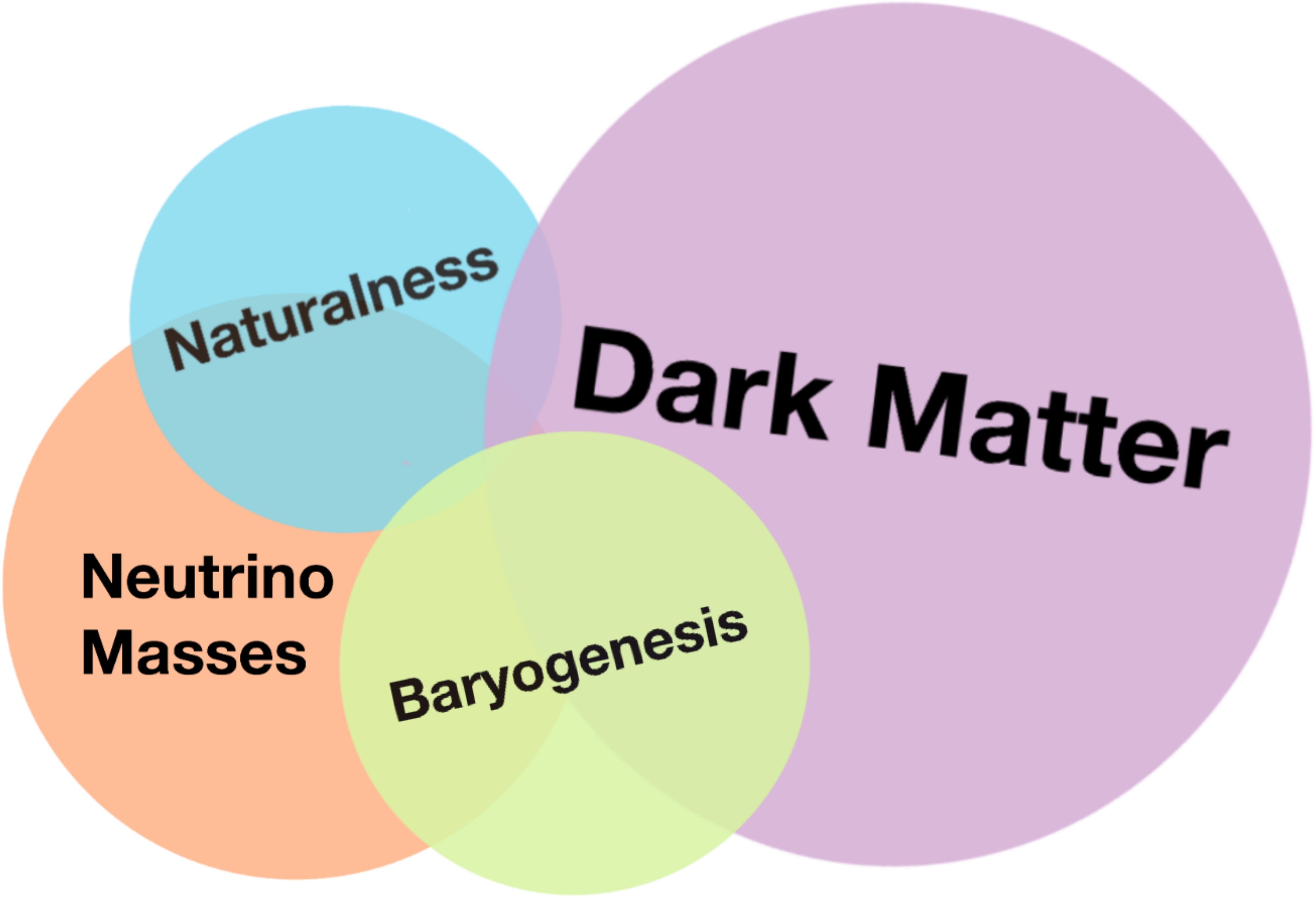


arXiv:1903.04497

- **SM particles all have different lifetimes**, even with similar masses
- Many of them are long-lived
  - Due to e.g. small couplings or a suppressed decay phase space
- But we use **Long-lived particles (LLPs)** as an umbrella term
  - New particles, that we have not discovered yet, with lifetimes long enough to travel measurable distances inside the detectors before decaying

Where do we get LLPs?

- The same conditions that make some SM particles long-lived are also present in BSM models
  - **LLPs are a generic signature of BSM physics, connected to central questions**
    - SUSY models, R parity violating (RPV) and conserving (RPC); exotic decays of the Higgs boson; Heavy Neutral Leptons (HNLs) connected to neutrino masses; dark matter candidates; or new scalars, such as dark photon or Axion-Like Particles (ALPs).
    - **In general, LLPs feature extensively in hidden sectors**
- If light (<1 GeV) new particles exist, they must be very weakly coupled → LLPs



LLP searches have been going on for years at
colliders in different ways
Looking for them is nothing new

One could say that Long-Lived Particles are living a Renaissance

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CERN-TH-2018-142
CP3-Origins-2018-023 DNRF90
FERMILAB-PUB-18-264-T
IFT-UAM-CSIC-18-060
IPMU18-0109
KIAS-P18052
LCTP-18-17
TTP18-022
ULB-TH/18-09
UMD-PP-018-04
YITP-SB-18-16

arXiv:1806.07396v2 [hep-ph] 5 Mar 2019

Long-Lived Particles at the Energy Frontier: The MATHUSLA Physics Case

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David Curtin[1], Marco Drewes[2], Matthew McCullough[3], Patrick Meade[4], Rabindra N. Mohapatra[5], Jessie Shelton[6], Brian Shuve[7,8].

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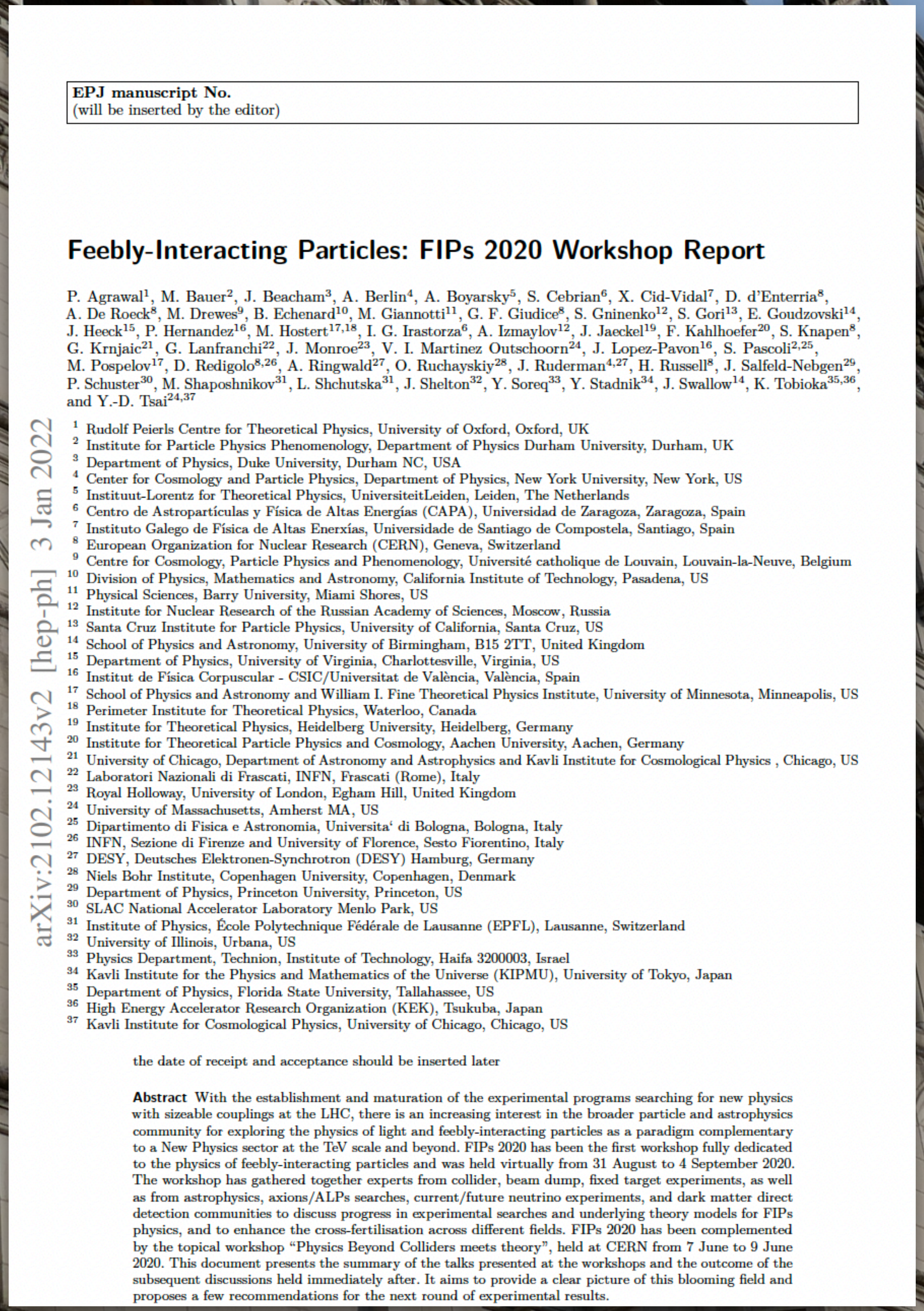

arXiv:2102.12143v2 [hep-ph] 3 Jan 2022

EPJ manuscript No.
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Feebly-Interacting Particles: FIPs 2020 Workshop Report

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Abstract With the establishment and maturation of the experimental programs searching for new physics with sizeable couplings at the LHC, there is an increasing interest in the broader particle and astrophysics community for exploring the physics of light and feebly-interacting particles as a paradigm complementary to a New Physics sector at the TeV scale and beyond. FIPs 2020 has been the first workshop fully dedicated to the physics of feebly-interacting particles and was held virtually from 31 August to 4 September 2020. The workshop has gathered together experts from collider, beam dump, fixed target experiments, as well as from astrophysics, axions/ALPs searches, current/future neutrino experiments, and dark matter direct detection communities to discuss progress in experimental searches and underlying theory models for FIPs physics, and to enhance the cross-fertilisation across different fields. FIPs 2020 has been complemented by the topical workshop "Physics Beyond Colliders meets theory", held at CERN from 7 June to 9 June 2020. This document presents the summary of the talks presented at the workshops and the outcome of the subsequent discussions held immediately after. It aims to provide a clear picture of this blooming field and proposes a few recommendations for the next round of experimental results.

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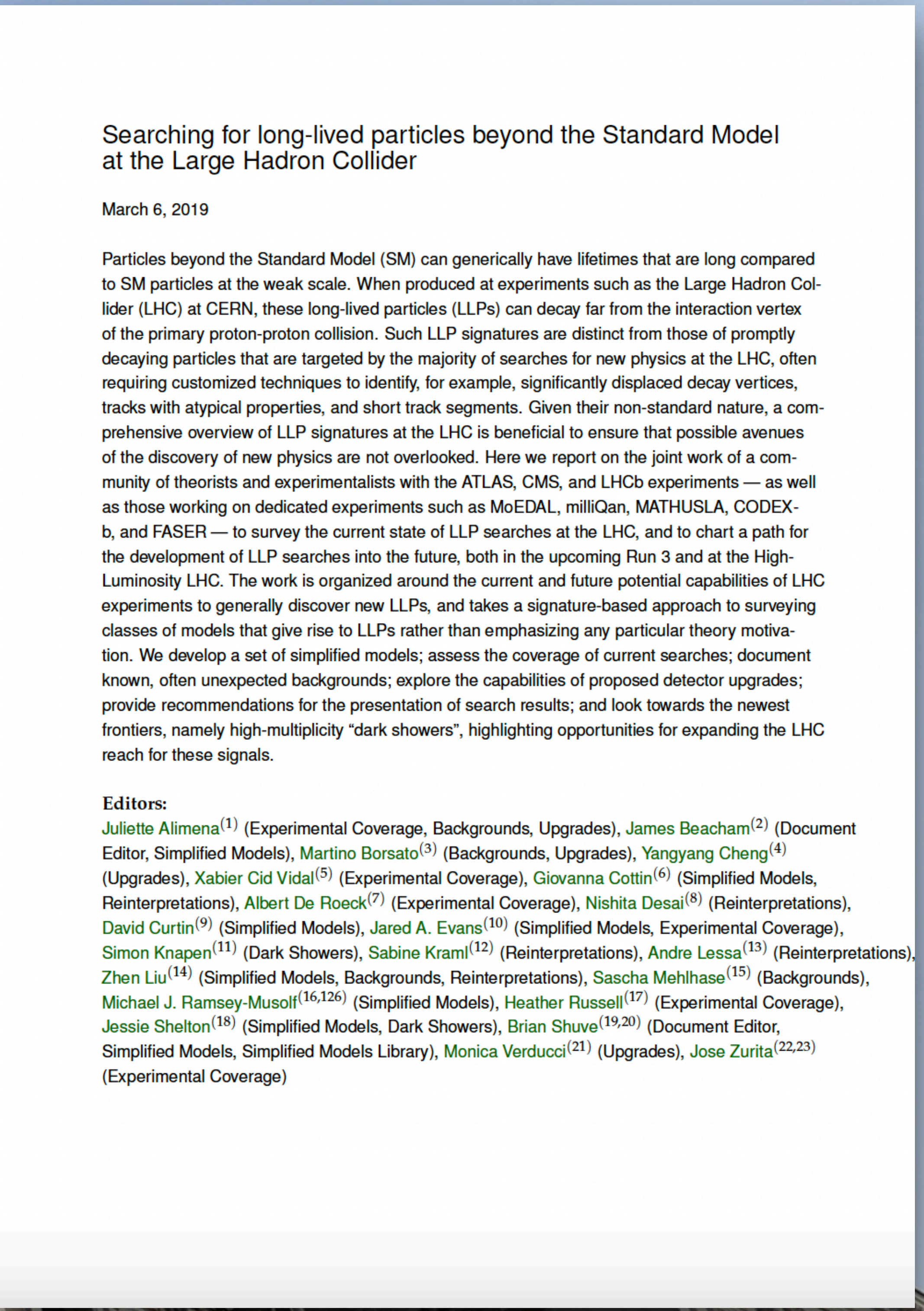

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matches for “long-lived” in the indico agenda
ICHEP 2012: 11
ICHEP 2022: 53


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Searching for long-lived particles beyond the Standard Model at the Large Hadron Collider
March 6, 2019
Searches for long-lived particles at the LHC: Workshop of the LHC LLP Community
24–26 Apr 2017
CERN
symmetry
dimensions of particle physics
Illustration by Sandbox Studio, Chicago with Ariel Davis
Long-lived particles get their moment
08/18/20 | By Sarah Charley
Scientists on experiments at the LHC are redesigning their methods and building supplemental detectors to look for new particles that might be evading them.
matches for “long-lived” in the indico agenda
ICHEP 2012: 11
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Though they never really died...

Why is this happening?

- There are a few reasons for why LLPs are so interesting nowadays:
  - Searches for LLPs **cover** intermediate areas where there is a **gap of sensitivity** between experiments (eg. dark matter searches between colliders and astro)
  - They can address the **lack of prompt BSM signals** → providing accessible new areas where BSM could be hiding
  - LLP searches offer us the opportunity to think outside the box, to be **creative** and to propose new ways to solve problems
    - **Innovation:** in methods and experimental setups

At high collision energies (LHC)

- We gain access to more massive particles that in turn tend to be shorter-lived

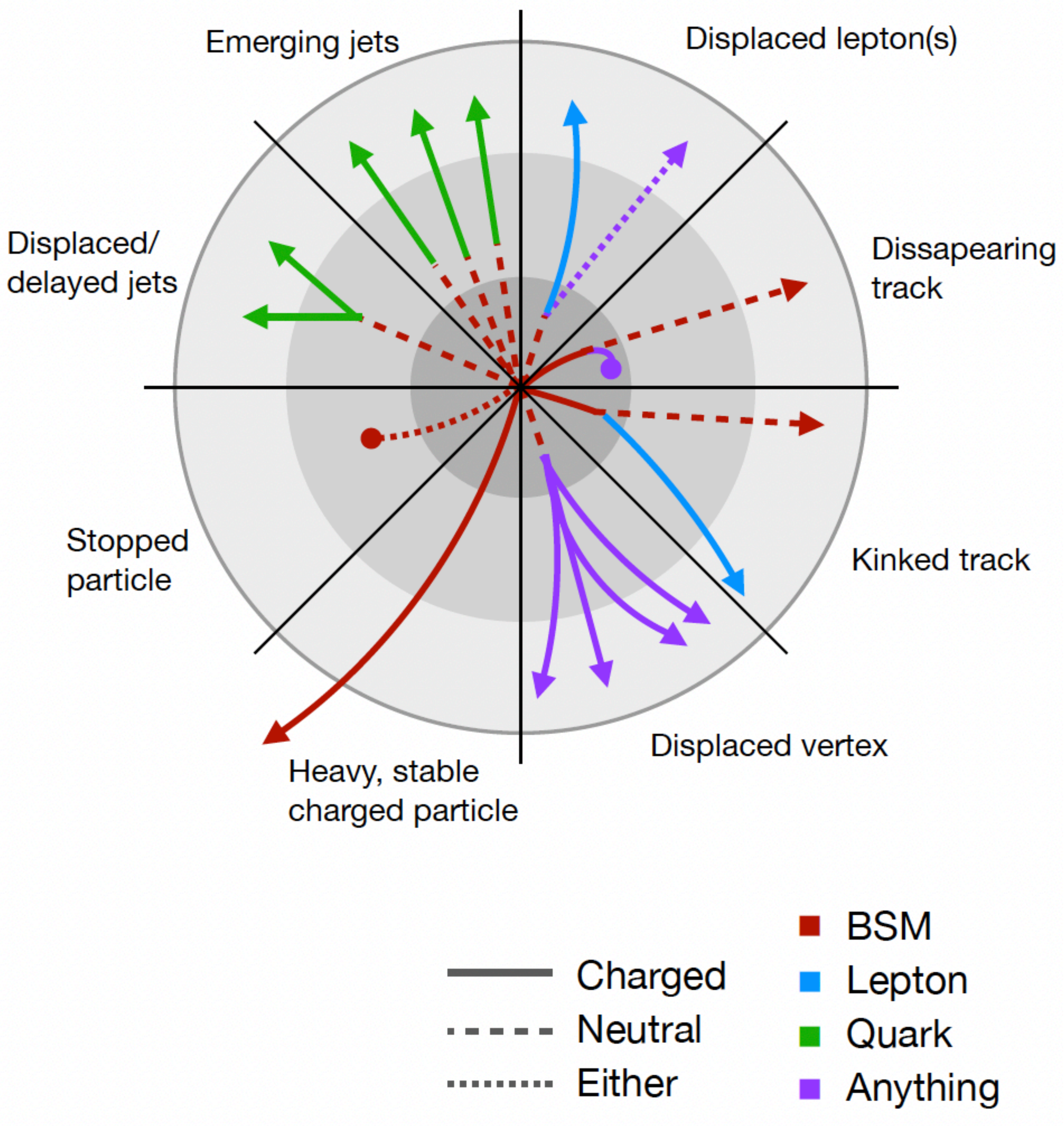
Main offenders

The Higgs boson
2012 - LHC
Sort-Lived
10^{-22} seconds
You blink and you miss it!

The top quark
1995 - Tevatron
Sort-Lived
10^{-25} seconds
So short-lived it does not even have time to form hadrons!

- And we naturally optimize our detectors, trigger, and reconstruction methods to find them
  - **LLPs could be regularly produced in collisions and we wouldn't know it**
- LLPs produce unconventional signatures in colliders
  - clearly different from other processes (easy to spot!), but potentially invisible to current data-acquisition methods → we could be throwing them away

Non-standard experimental signatures



- When produced in collisions at the LHC, LLPs can either completely pass through the detectors before decaying or decay inside them in unconventional signatures:
  - displaced and/or delayed objects (leptons, photons, jets); disappearing tracks; nonstandard tracks produced by monopoles, quirks or heavy stable charged particles (HSCPs); nonstandard jets produced in dark showers…
- LLP analyses at the LHC IP experiments:
  - require customisation: dedicated triggers, object reconstruction, background estimation and in general analysis methods
  - are affected by challenging backgrounds near the collision points → motivate dedicated experiments

LLPs, shopping list

- Implementing custom detectors, triggers and methods for LLPs pays off
    - If any of those experimental signatures is observed → smoking gun for new physics
    - **Signature-driven searches**

- **What do we need?**
    - ☑ Dedicated **triggers**
    - ☑ Hermetic detectors, large active volumes, to maximise geometric **acceptance**
    - ☑ High granularity at large radii for reconstruction efficiency of displaced tracks/vertices
    - ☑ Particle **reconstruction** capabilities for displaced objects
    - ☑ Particle **ID** capabilities: **dE/dx**, time-of-flight, good **vertex** & **timing** resolution
    - ☑ **Shielding**: for background mitigation

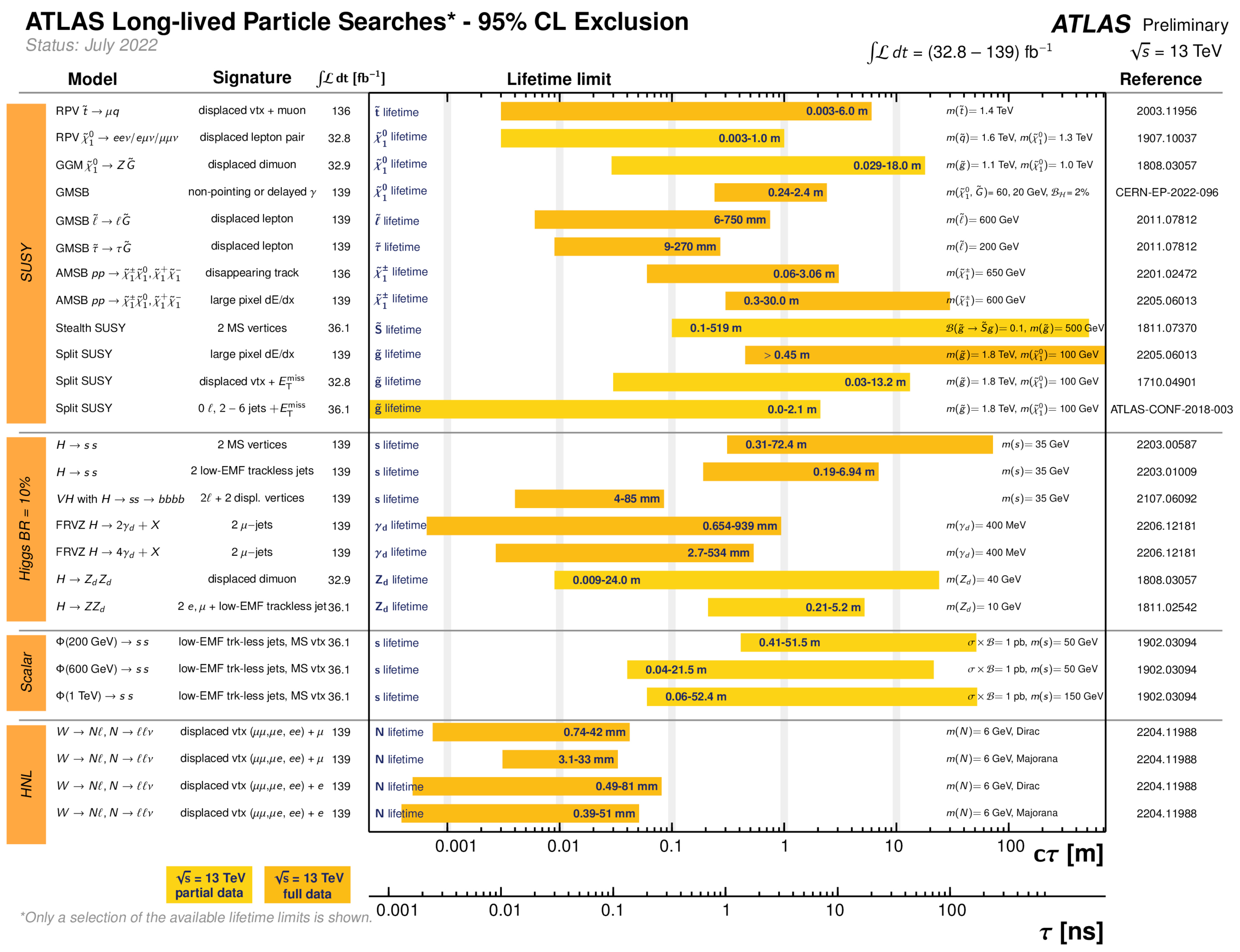
What do we have?

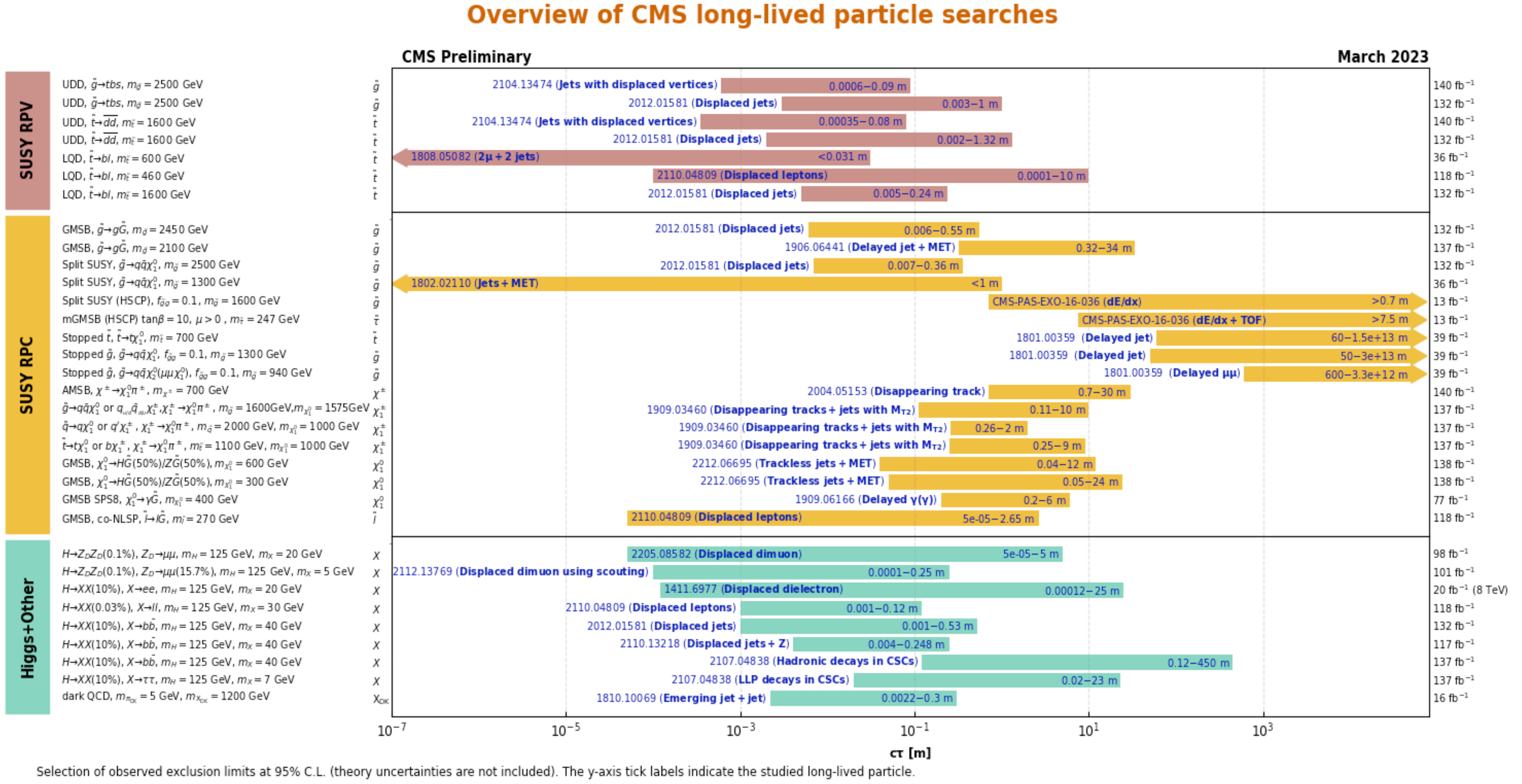
LLPs at the LHC


LHCb
ATLAS EXPERIMENT
CERN Meyrin
PS 628 m
CERN Prévessin
SPS 7 km
SUISSE
FRANCE
CMS
ALICE
LHC 27 km

ATLAS and CMS

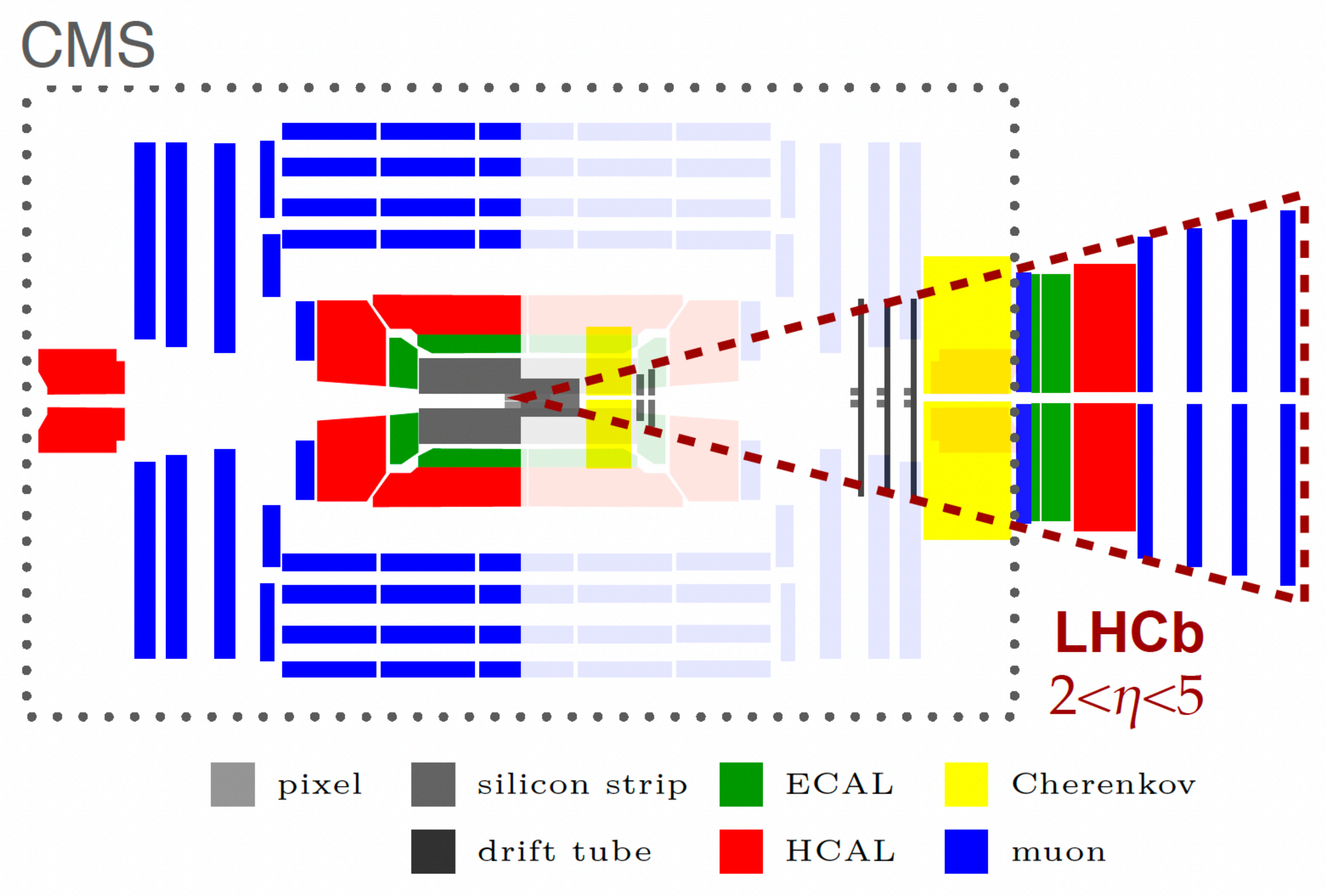
- Vibrant scene of long-lived searches in the exotics and SUSY groups
- Dedicated talk "Status of searches in the long-lived particles and dark sectors" by Marianna Liberatore on Tuesday [link]
- CMS results on Thursday by Soham Bhattacharya [link]

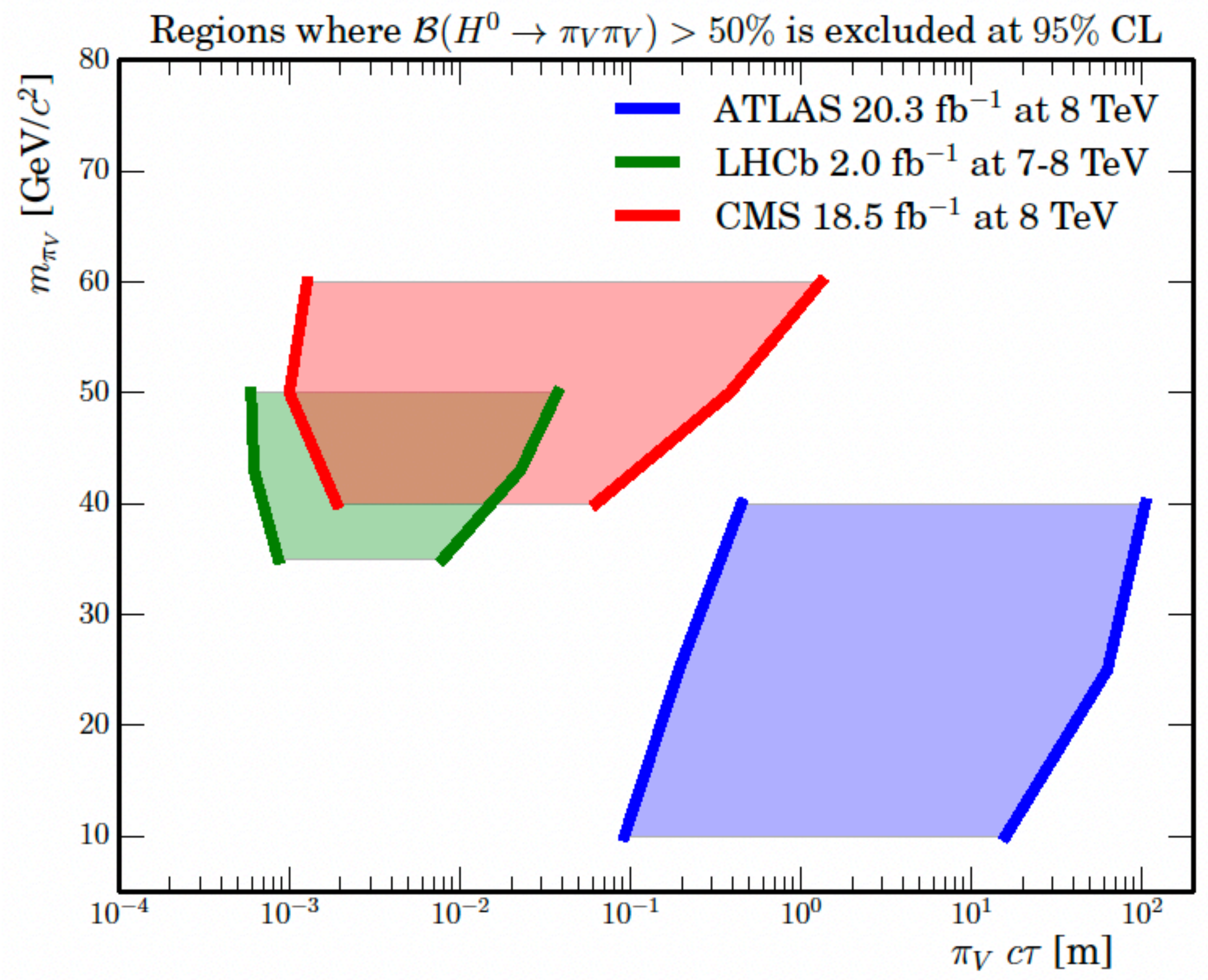




LHCb

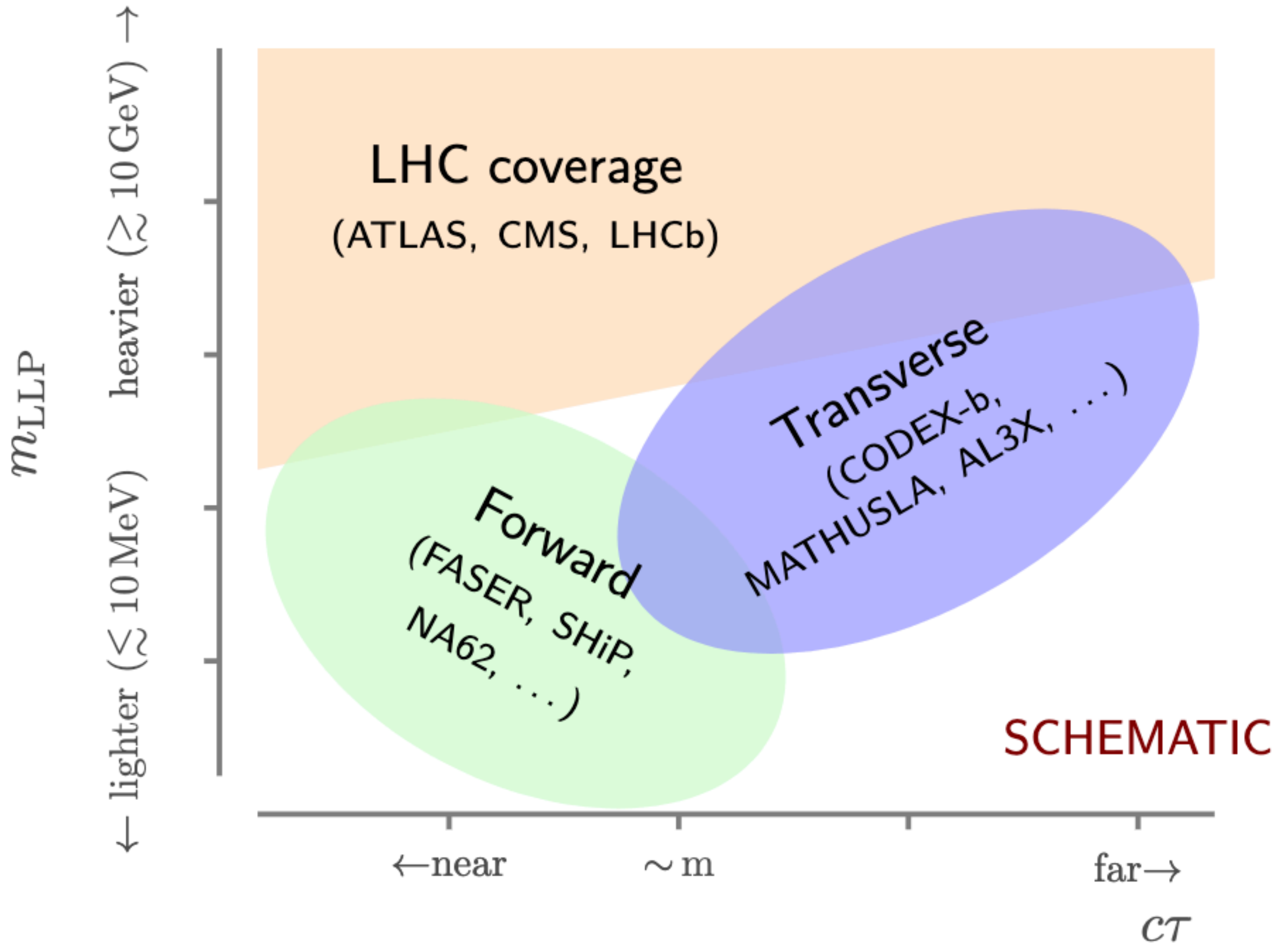
- Existing results on dark photons, exotic Higgs decays, HNLs [link]
- Complementary coverage to ATLAS and CMS
- First fully GPU trigger in HEP opens new possibility for LLPs
- New algorithms for downstream tracking and SciFi seeds could extend the reach of LHCb to decay lengths of ~6 m from the IP

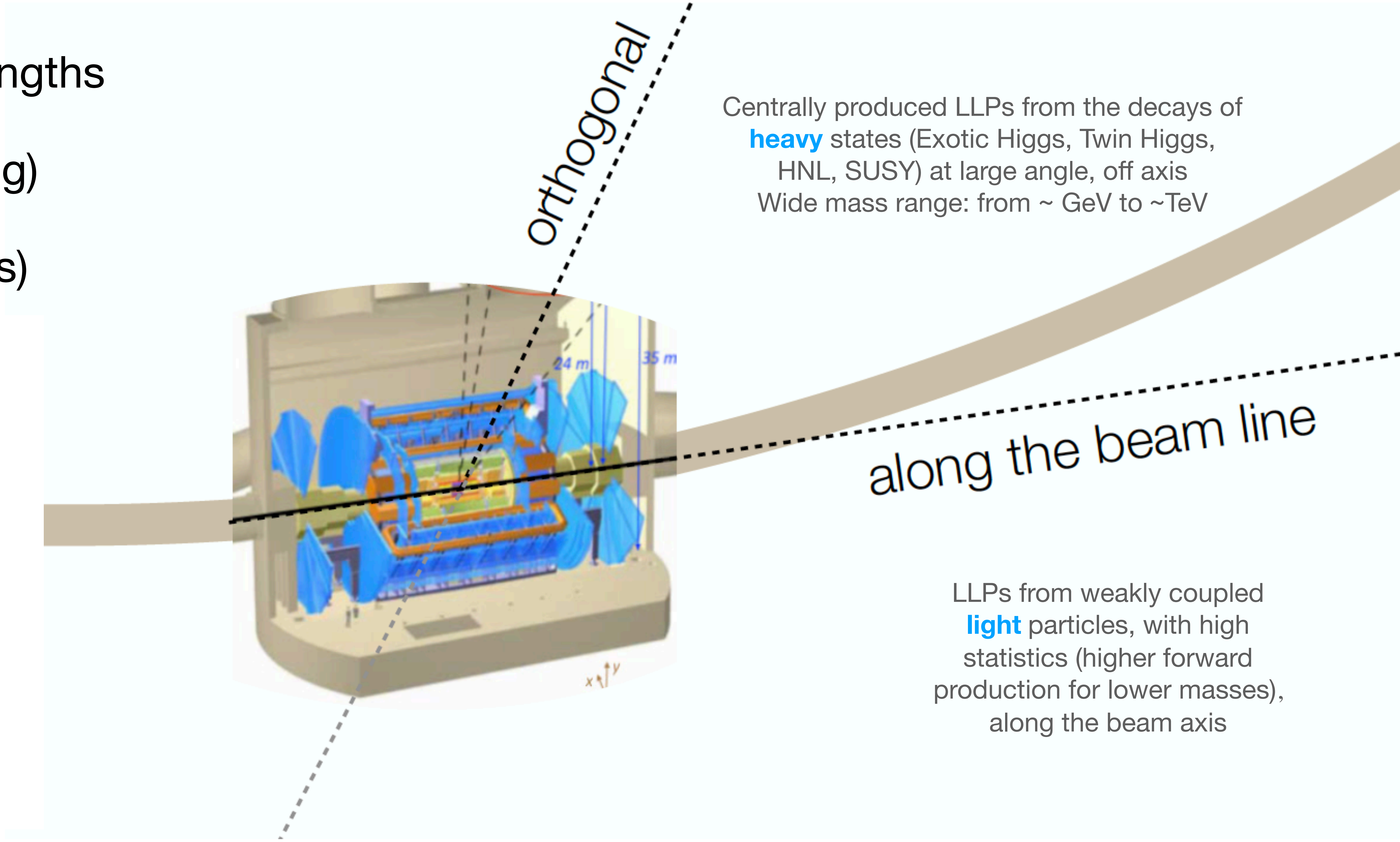




Thinking outside the LHC detectors

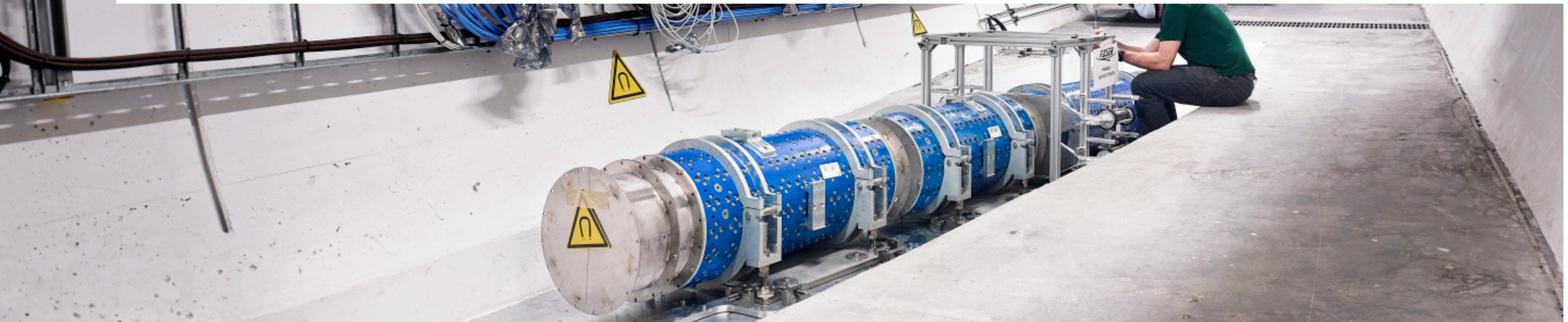
- We can supplement them with external detectors optimized for LLPs
  - Access to longer decay lengths
  - Less background (shielding)
  - Easy trigger (or trigger-less)

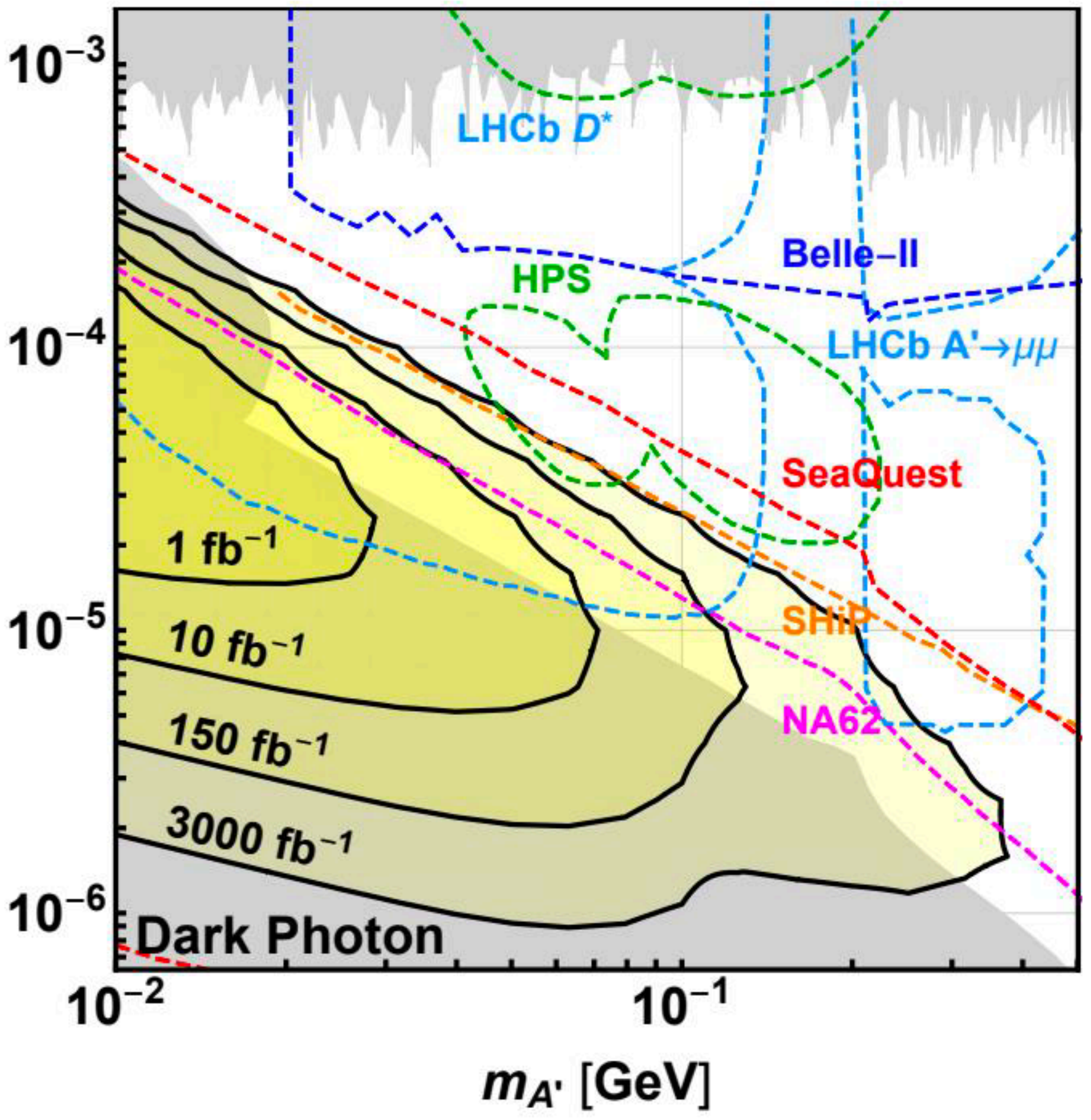




FASER

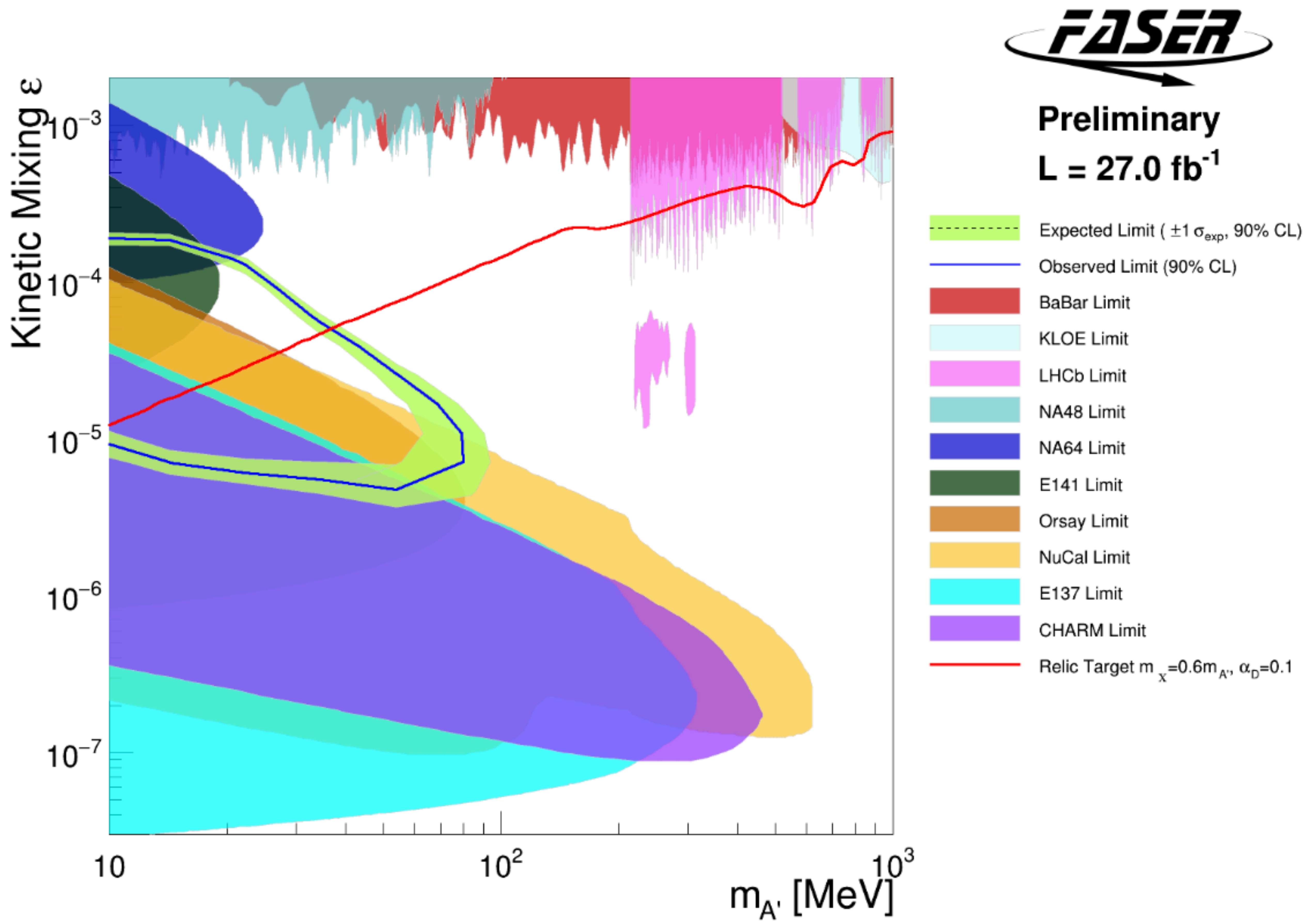
- ForwArd Search ExpeRiment, ~1 m³ 480 m downstream from the ATLAS interaction point (on-axis)
- https://faser.web.cern.ch/
- Approved in 2019, Installed during the Long Shutdown 2 - **Taking data!**
- Designed to detect LLPs produced at the ATLAS Interaction Point in the forward region
  - For highly collimated and extremely weakly coupled particles
  - decay products ~ TeV energies
- Sensitivity to dark photons, HNLs, ALPs …
  - *pp* → LLP + X,   LLP travels ~480 m,   LLP → charged tracks + X





First results from FASER

- First observation of collider neutrino events: arXiv:2303.14185
- First limits on previously unconstrained regions of dark photon parameter space:
  - https://cds.cern.ch/record/2853210/
- Talk by Charlotte Cavanagh: [link]



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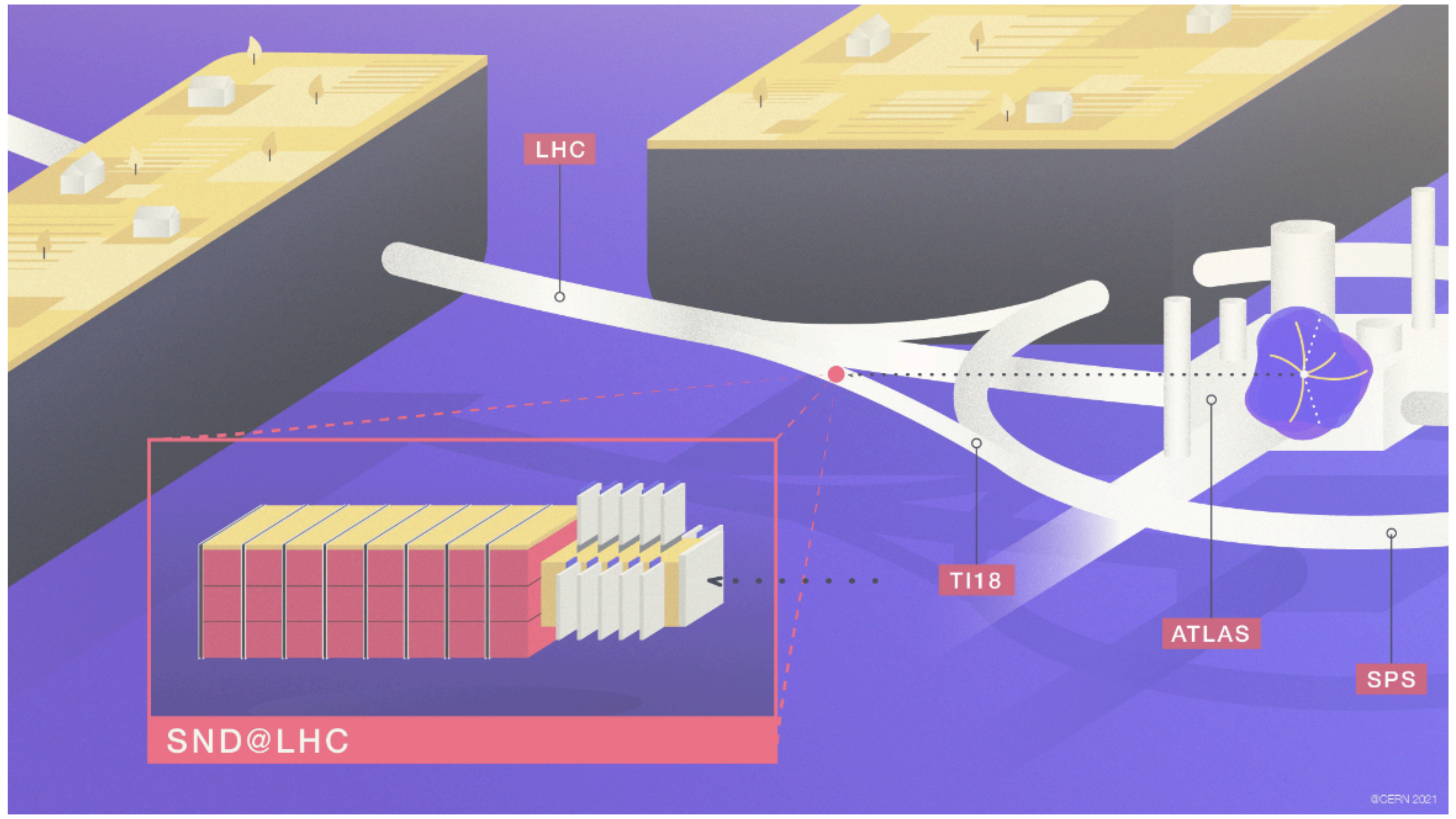
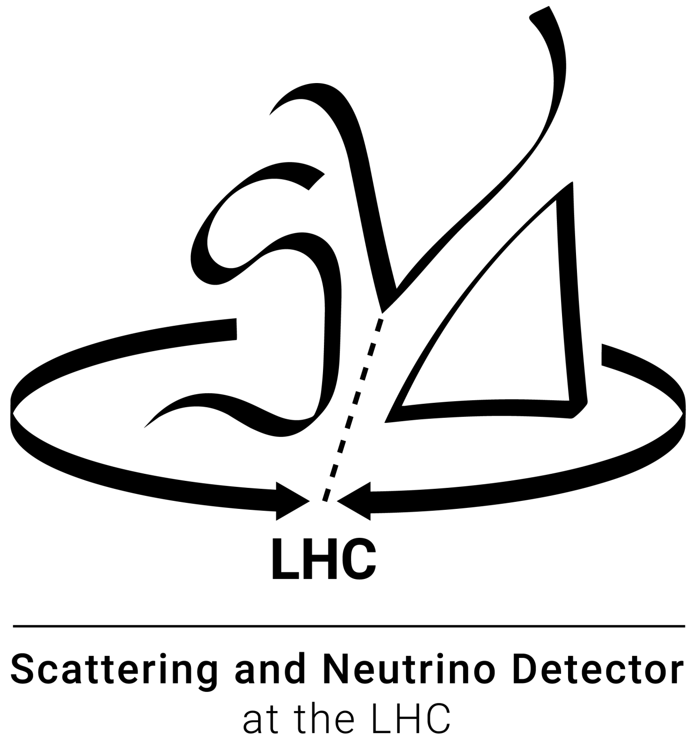
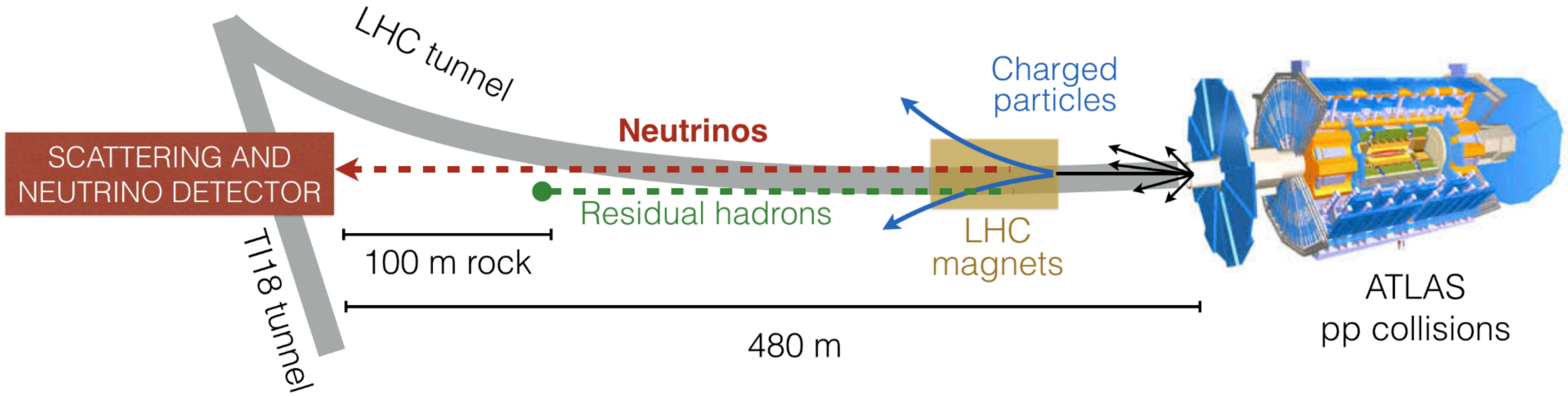
SND@LHC

- Neutrino experiment approved in 2021, installed, commissioned and taking data since the start of Run-3
- https://snd-lhc.web.cern.ch/
- 480 m from the ATLAS collision point (on the other side), 100 m of rock shielding
- Diverse neutrino physics program, can also probe LLPs in Hidden Sector models
- Talk by Carlo Battilana [link]



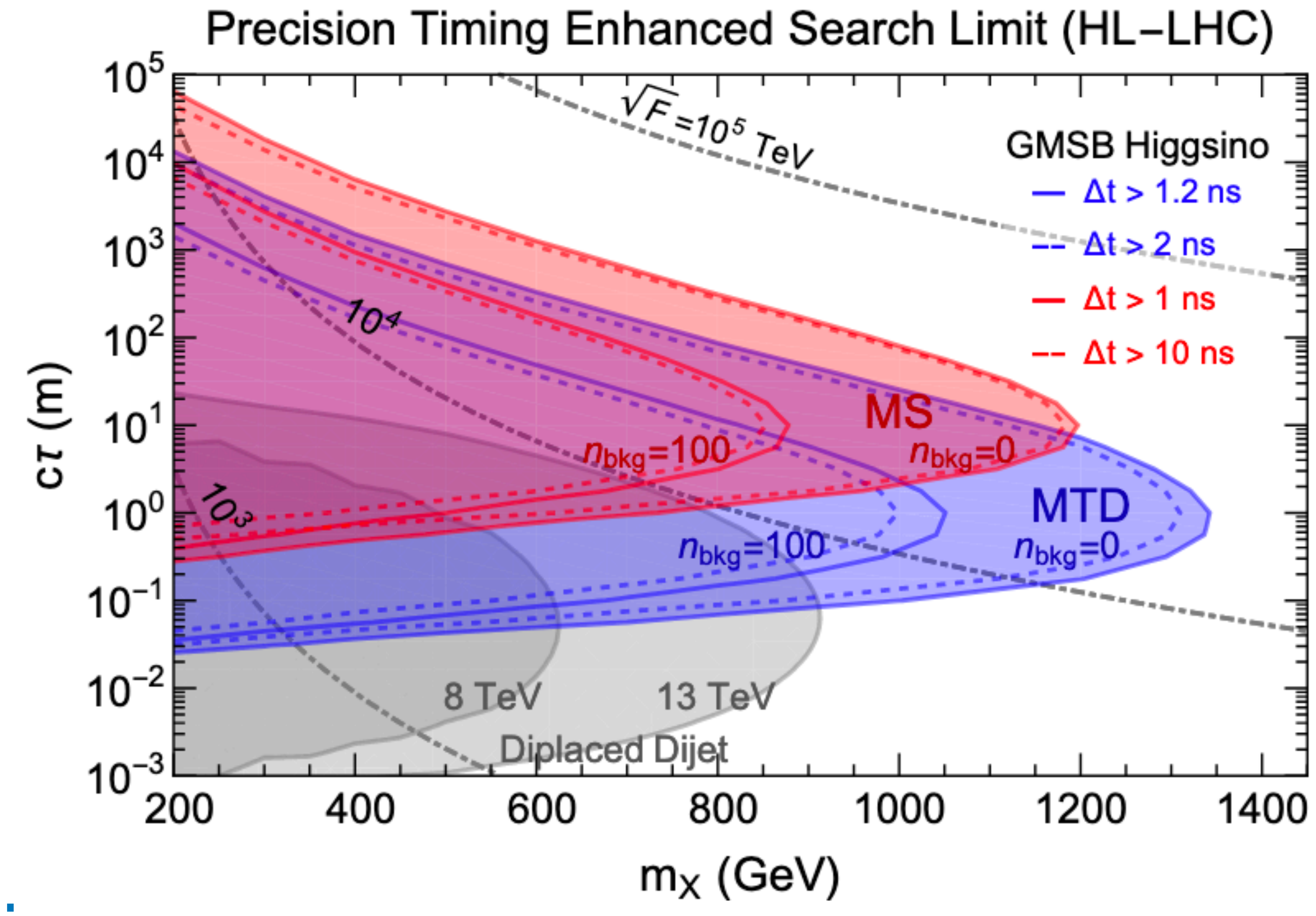


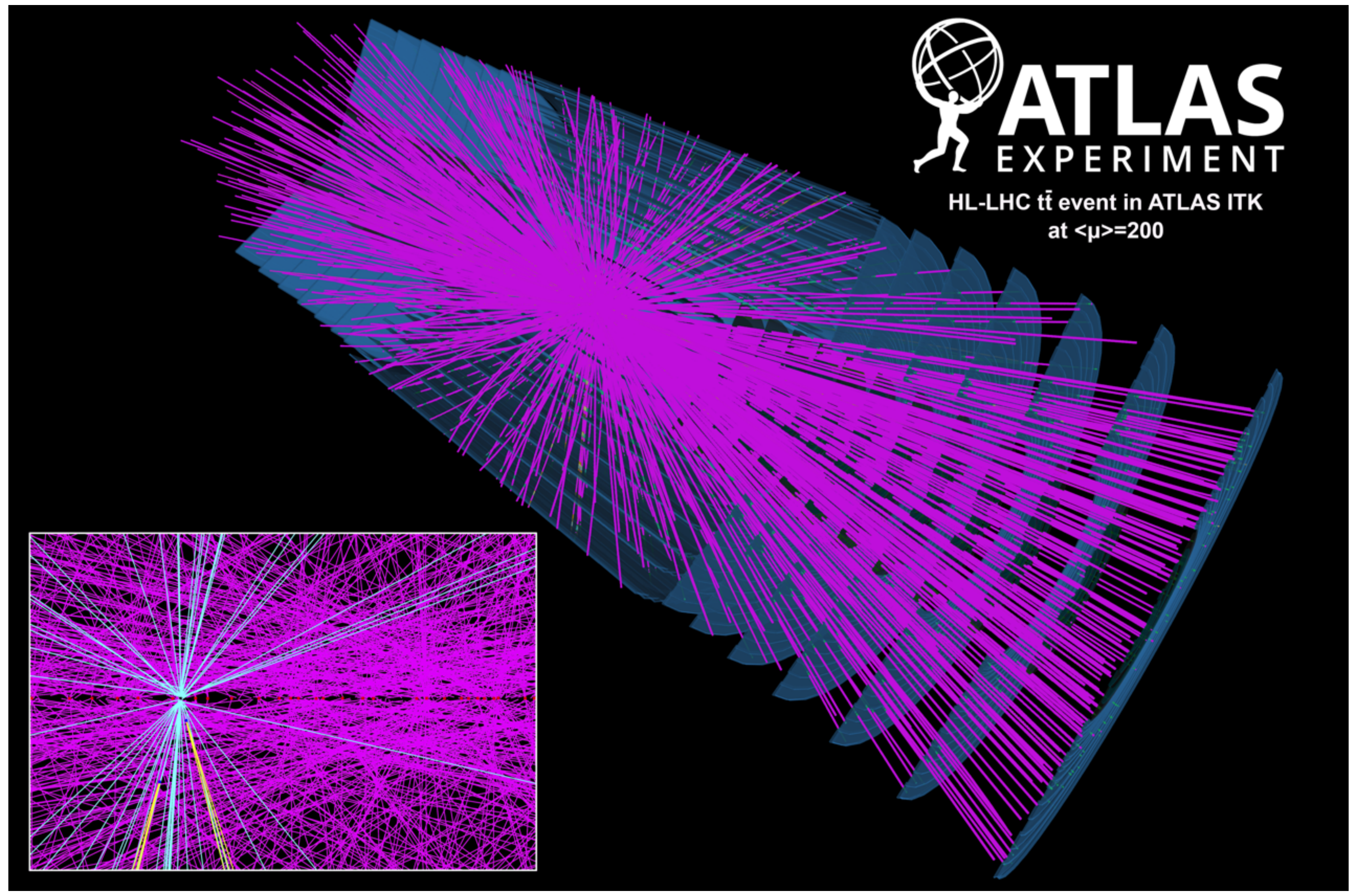


LLPs beyond the LHC

First stop: HL-LHC

- High luminosity comes with high pile-up, ~200 pp collisions are expected every 25 ns (Vs. ~36-37 in Run-2)
- Neither track reconstruction or trigger are going to get any easier





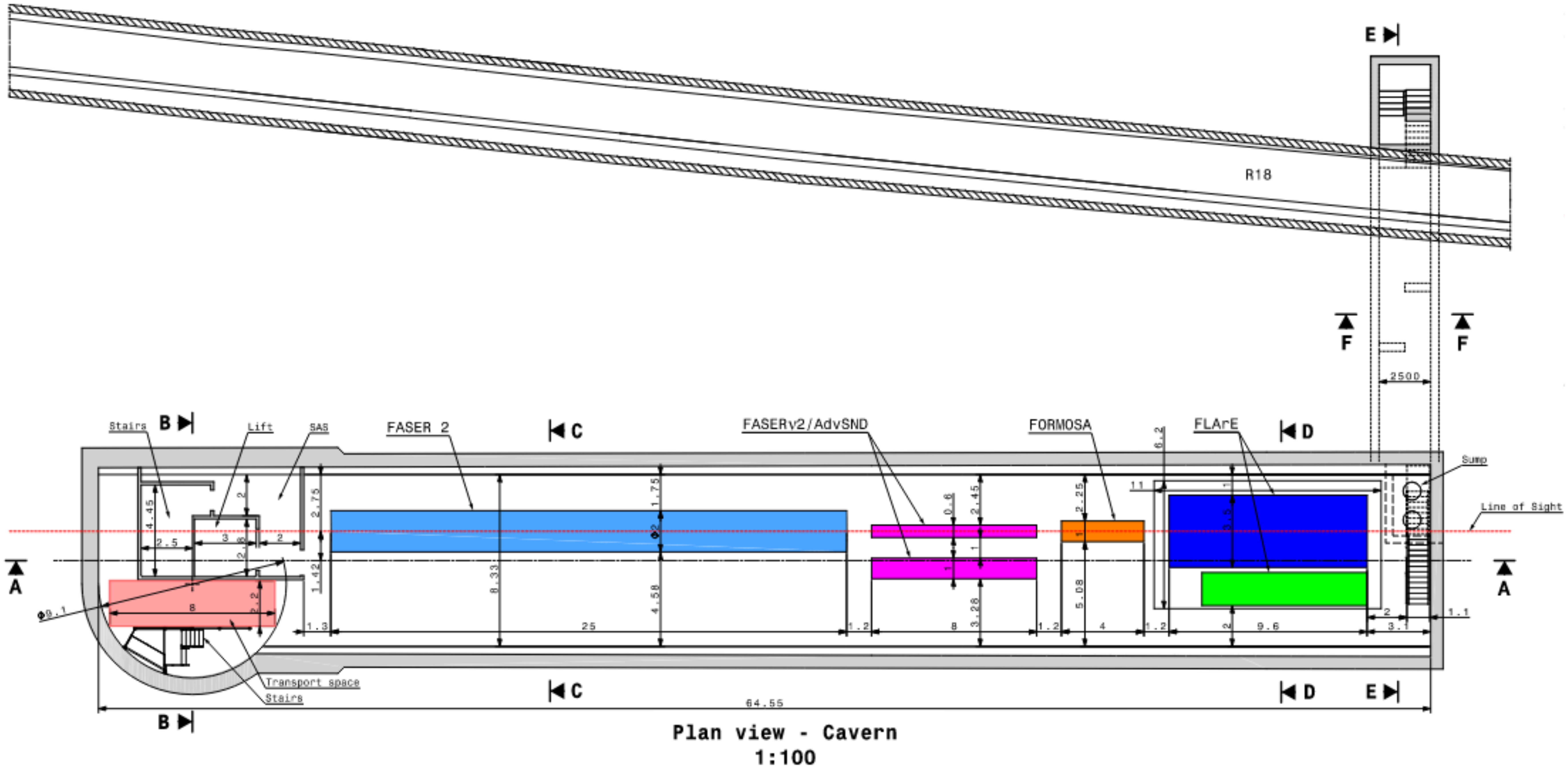
- New functionalities
  - **Track triggers** (arXiv:1907.09846): e.g. trigger on displaced muons from the same vertex to find dark photons (arXiv:1705.04321)
  - Better **timing information**: using timing information to target pair-produced LLPs significantly delayed (arXiv:1805.05957)

HL-LHC: Dedicated experiments

- MATHUSLA: (proposed) large-scale surface detector instrumenting ~$8\times10^5 m^3$ above ATLAS or CMS (off-axis) arXiv:2009.01693 website
  - Constructing a 64-channel, 4-layer prototype at University of Victoria
- CODEX-b: (proposed) ~$10^3 m^3$ detector in the LHCb cavern (off-axis) arXiv:2203.07316 git
  - Building of CODEX-β demonstrator unit ongoing.
- AL3X: (proposed) cylindrical~900 m^3 detector inside the L3 magnet and the time-projection chamber of the ALICE experiment (on-axis) arXiv:1810.03636
- ANUBIS: (proposed) 1×1 m^2 units on top of ATLAS/CMS (off-axis) arXiv:1909.13022 twiki
  - The proANUBIS prototype just been installed in the ATLAS experimental cavern
- FACET: (proposed) ~100m in front of CMS (on-axis). Large decay volume (50 m) arXiv:2201.00019

FPF

- FASER and SND@LHC: highly constrained by 1980's infrastructure that was never intended to support experiments
- Proposed dedicated Forward Physics Facility (FPF) for the HL-LHC



More LLP experiments at the LHC

- Beam dump using the SPS proton beam line in the North area
  - NA62: (running) fixed-target experiment, kaon and beam-dump physics program with sensitivity to hidden sector (dark photon/Higgs, ALPs, HNLs..)
  - SHiP: (proposed) Intensity-frontier wide-spectrum (~GeV-scale) FIP search, zero-background reachable
  - SHADOWS: (proposed) competitive to CODEX-b and FASER2 for FIPs from charm/beauty
- Experiments for exotic electromagnetic charge:
  - MilliQan: (demonstrator taking data) searching for dark-sector millicharged particles with feeble coupling strength in the drainage gallery of CMS
  - MoEDAL-MAPP: (running) First LHC dedicated search experiment! looking for highly ionizing particles like magnetic monopoles at LHCb, upgrade with sensitivity to millicharged particles, SUSY LLP states, and even HNLs
  - FORMOSA: (proposed) millicharged particles in the 10 MeV to 100 GeV mass range using the FPF
- Many other experiments can also search for LLPs, e.g. Neutrino experiments, B-factories or dark matter experiments.

And then?

After the HL-LHC

2020 European Strategy Update

"An electron-positron Higgs factory is the highest-priority next collider.

For the longer term, the European particle physics community has the ambition to operate a proton-proton collider at the highest achievable energy."

(European Strategy Update brochure)

Snowmass 2021

"The intermediate future is an e^+e^- Higgs factory, either based on a linear (ILC, C3) or circular collider (FCC-ee, CepC).

In the long term EF envision a collider that probes the multi-TeV scale, up or above 10 TeV parton center-of-mass energy (FCC-hh, SppC, Muon Coll.)"

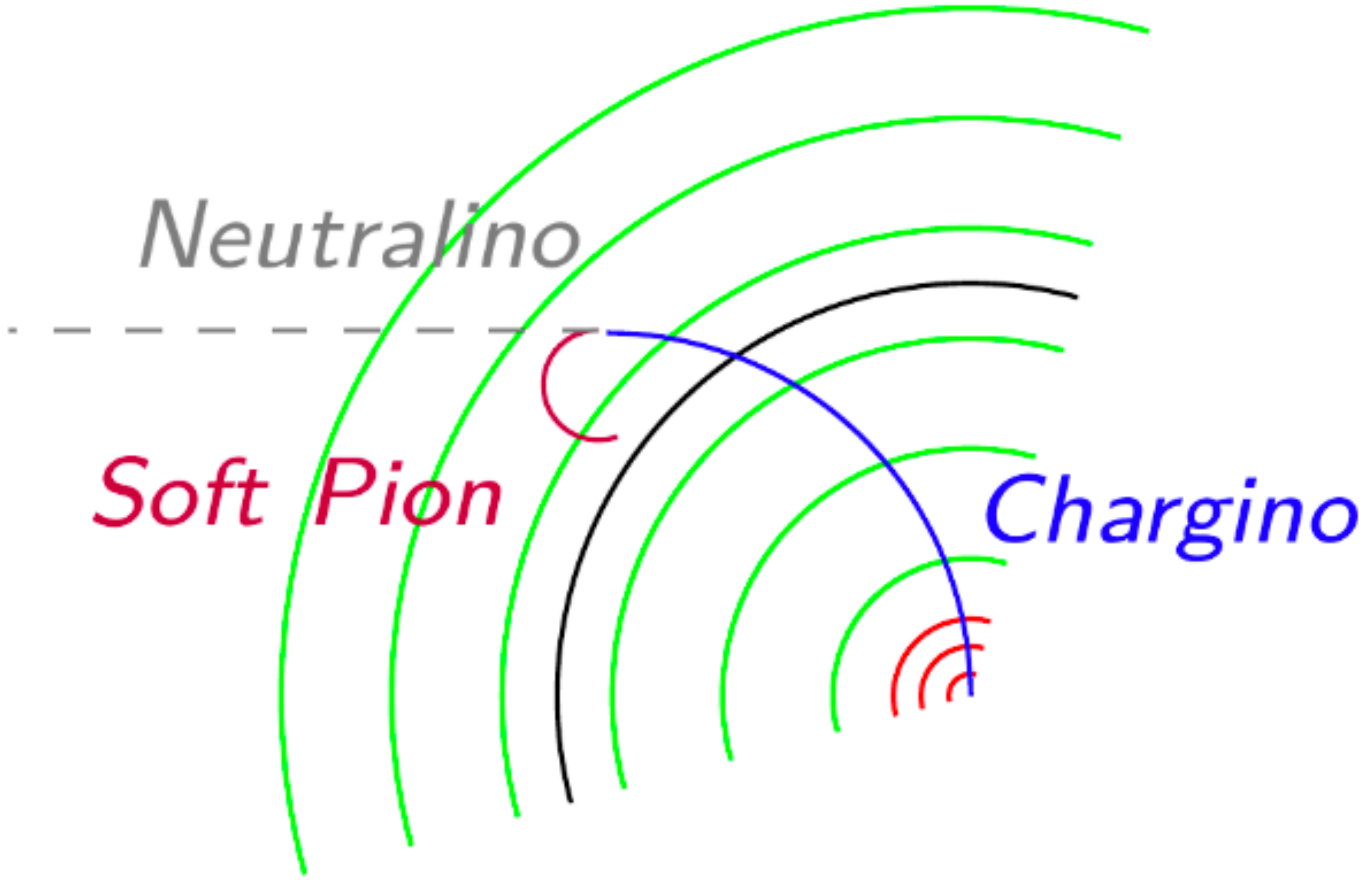
(Energy Frontier Plenary by Alessandro Tricoli)

1st physics case right off the bat for LLPs: Exotic Higgs decays

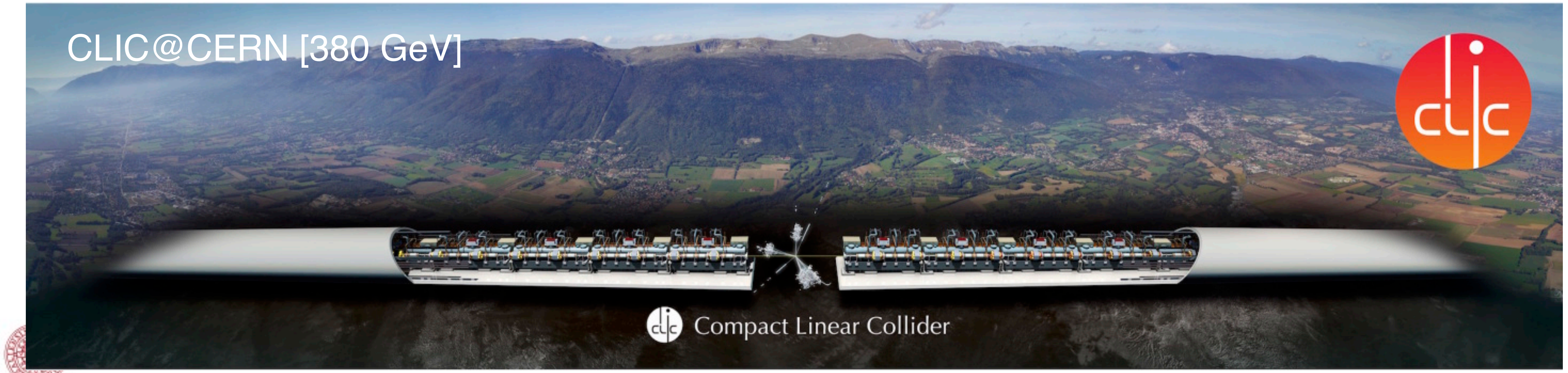
Ryu Sawada

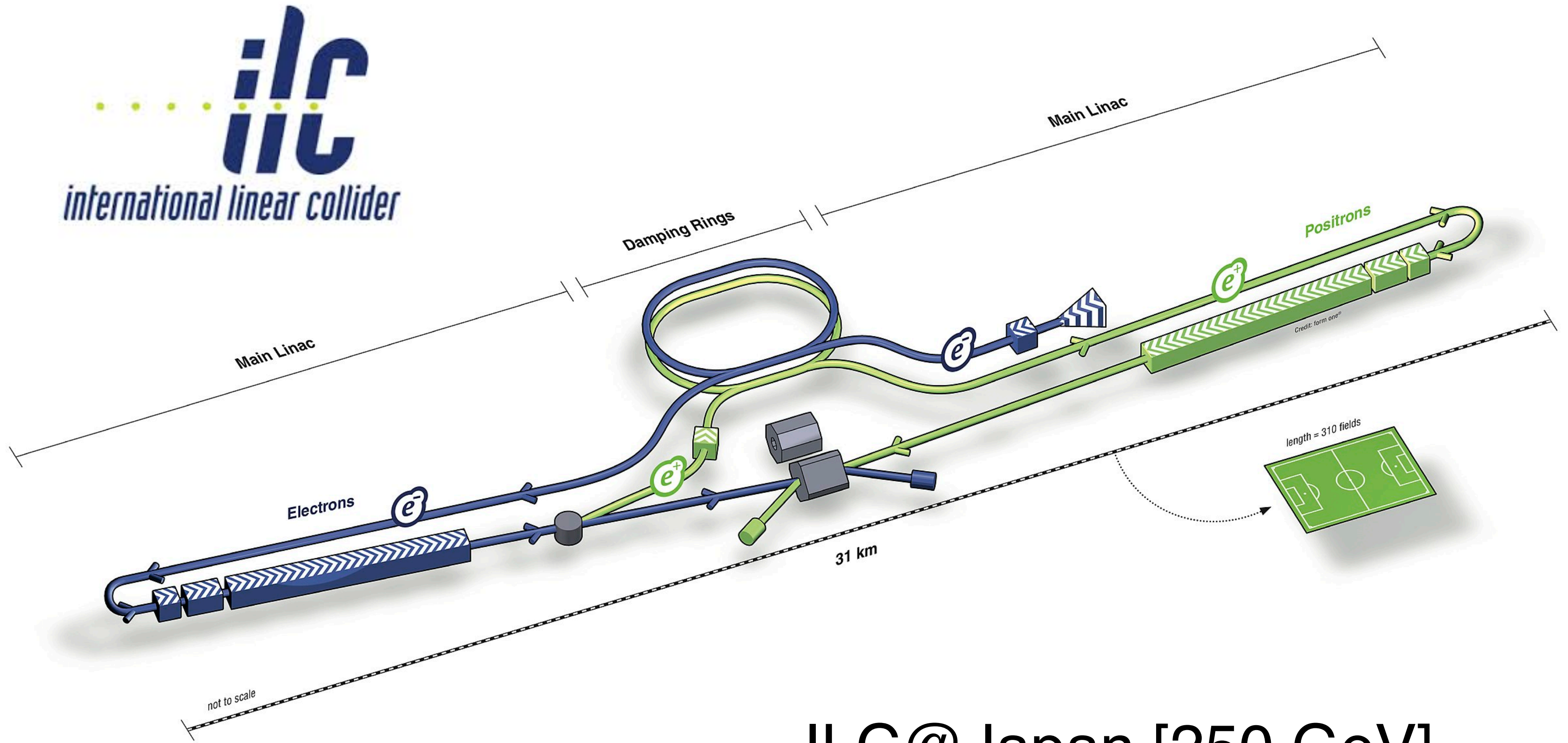
Linear e+e- Colliders

- **CLIC:** (https://agenda.linearcollider.org/event/8217/contributions/44770/)
  - Hidden valley searches in Higgs boson decays with displaced vertices (https://cds.cern.ch/record/2625054)
  - Degenerate Higgsino Dark Matter → chargino pair production (disappearing tracks) (arXiv:1812.02093, arXiv:1812.06018)



https://clic.cern/

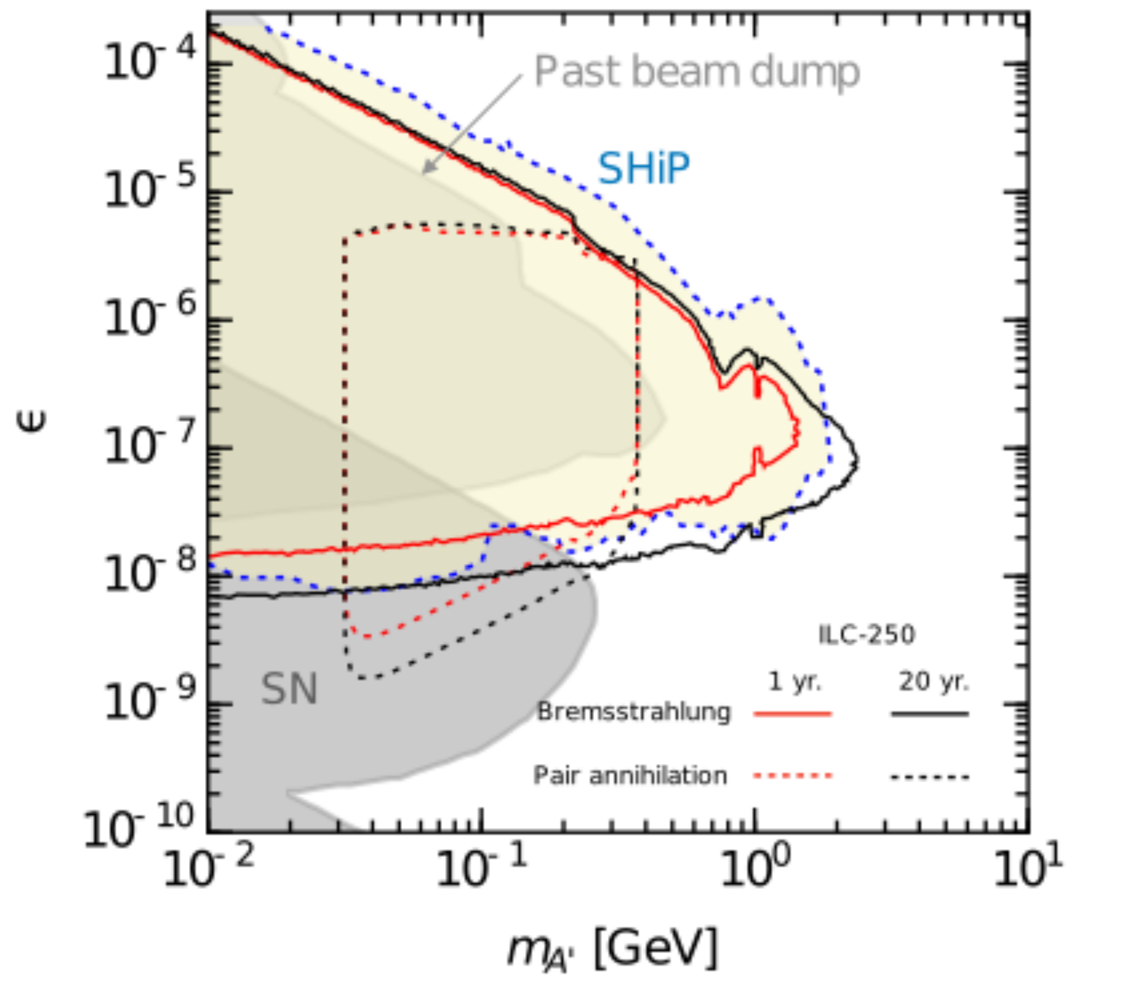




ILC@Japan [250 GeV]

Beam dump experiments at linear colliders

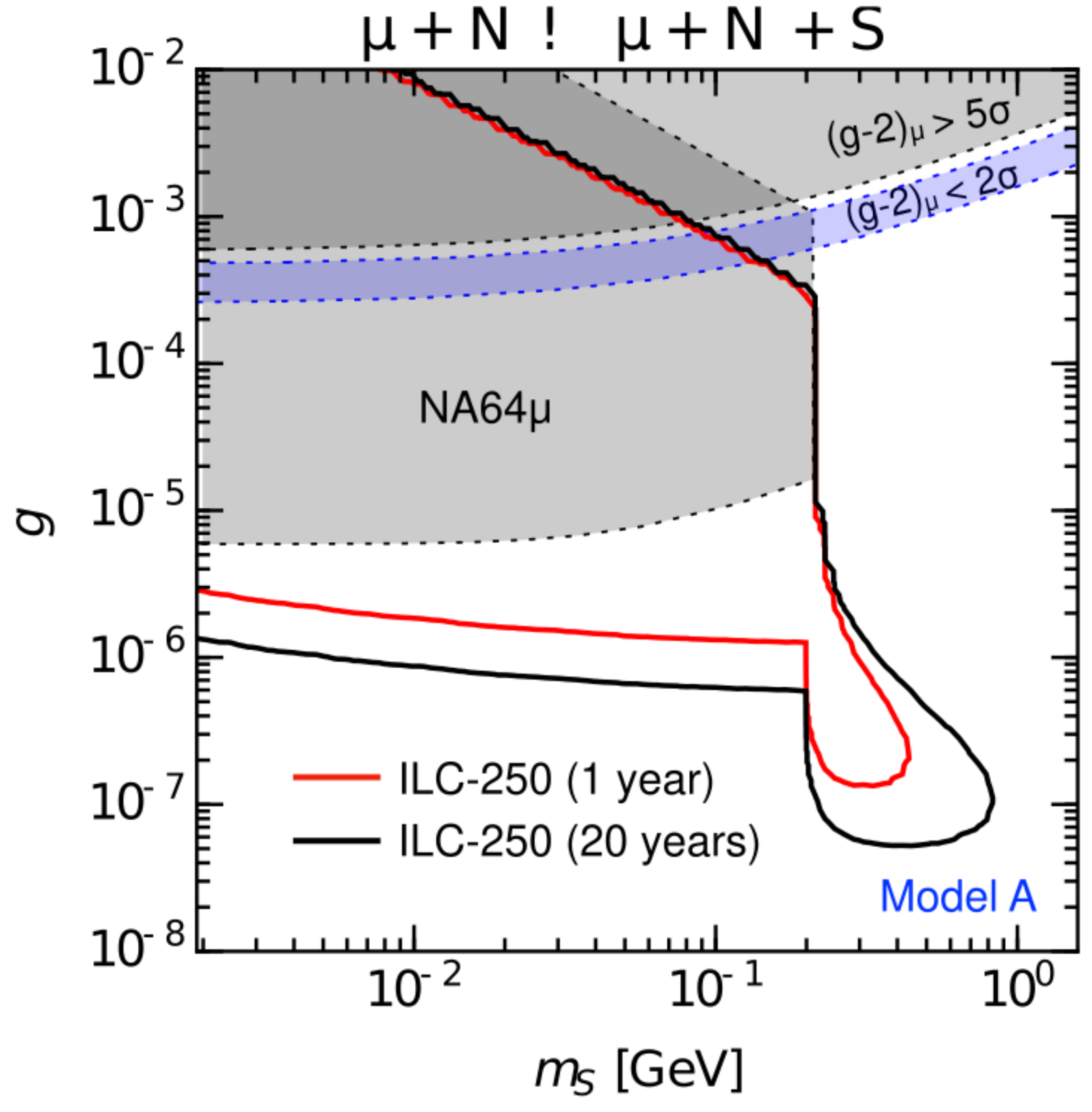
arxiv:2105.13768



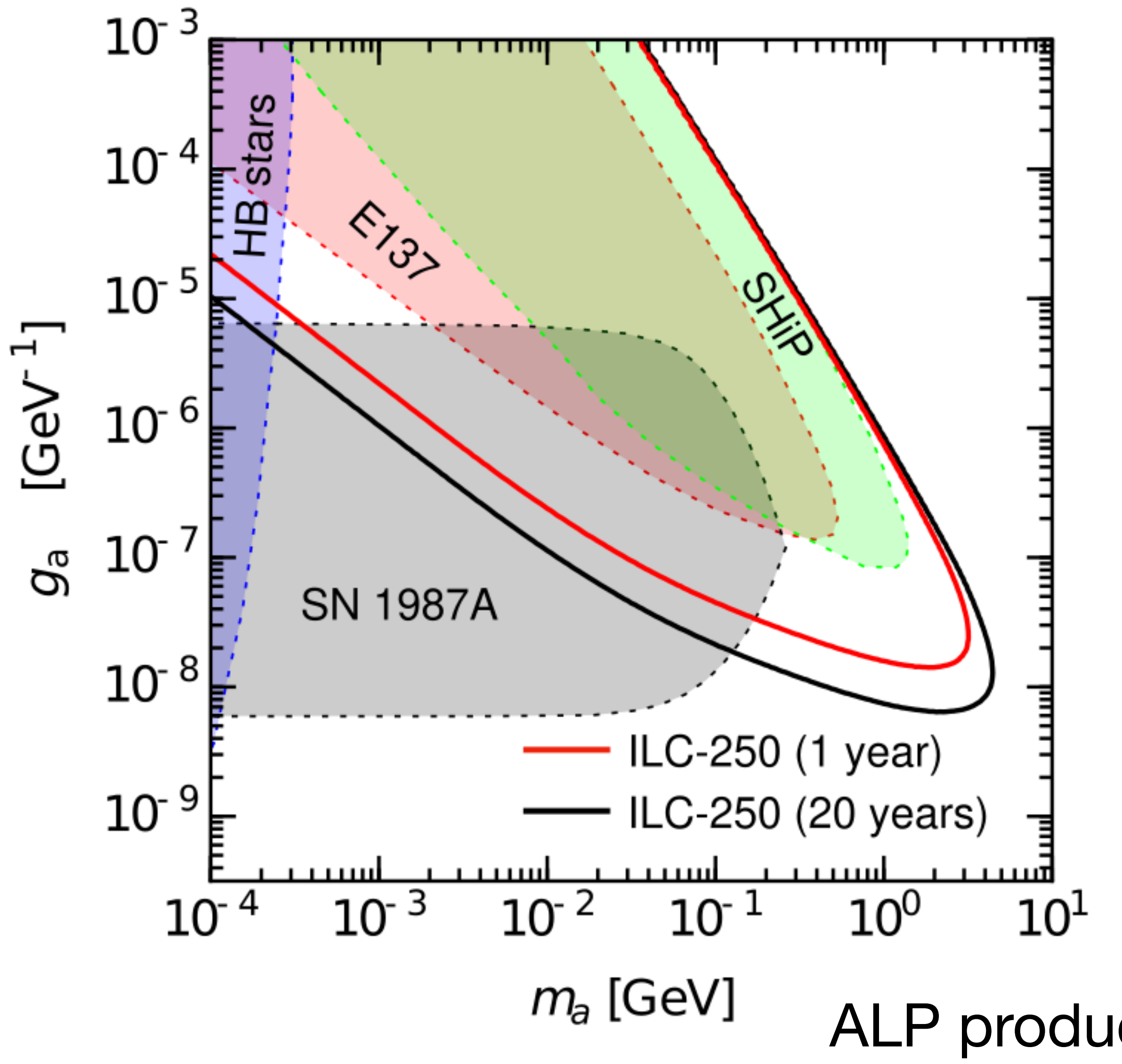
- At linear colliders extreme intensities expected at electron and positron beam dumps open unique options for fixed-target experiments focused on rare processes.
- ALPs, new scalars or dark photons

Dark Photon decays:
← invisible and visible ↑

arxiv:2009.13790

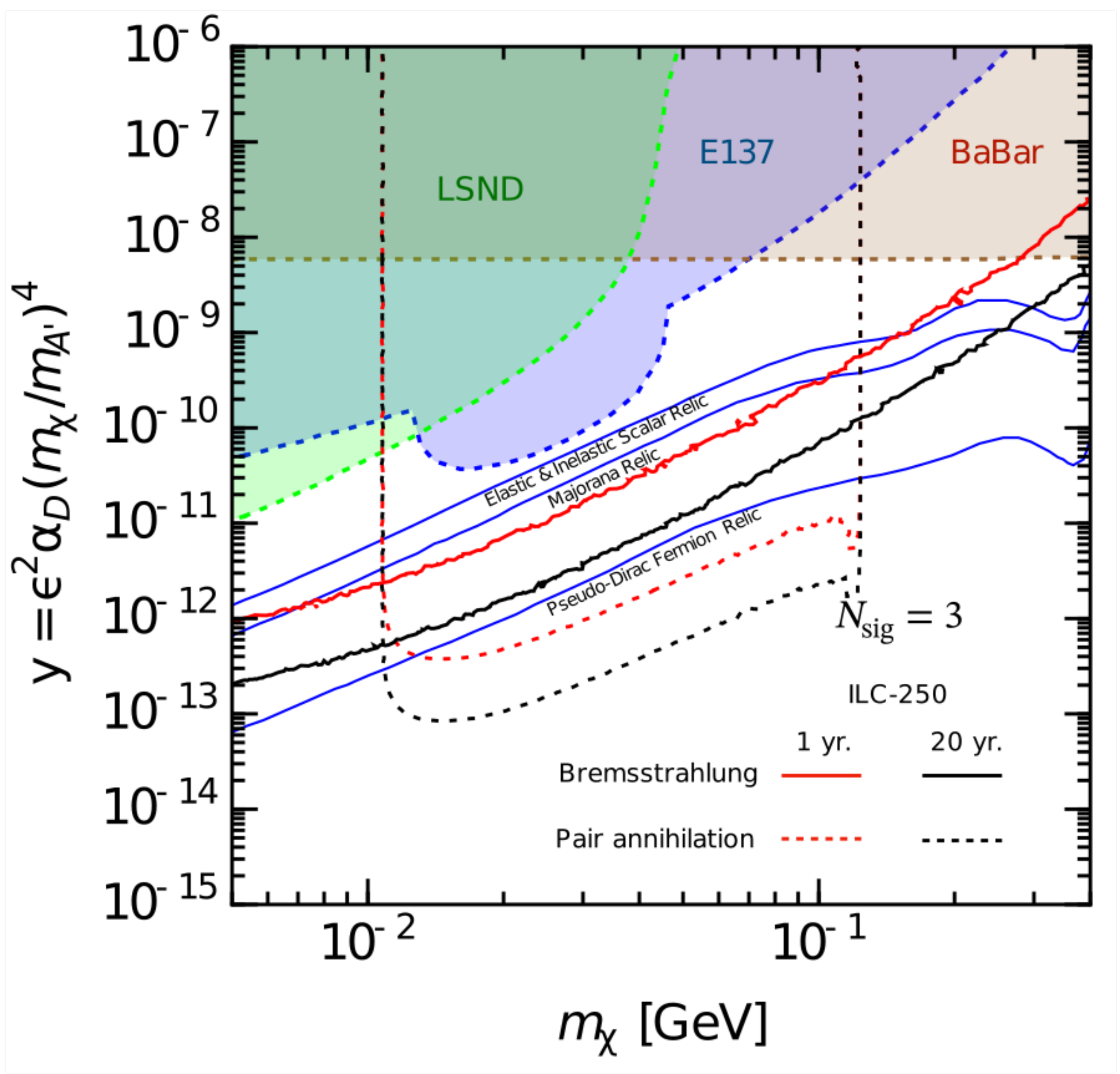


New scalars



ALP production

D.Ueda @ ILCX2021



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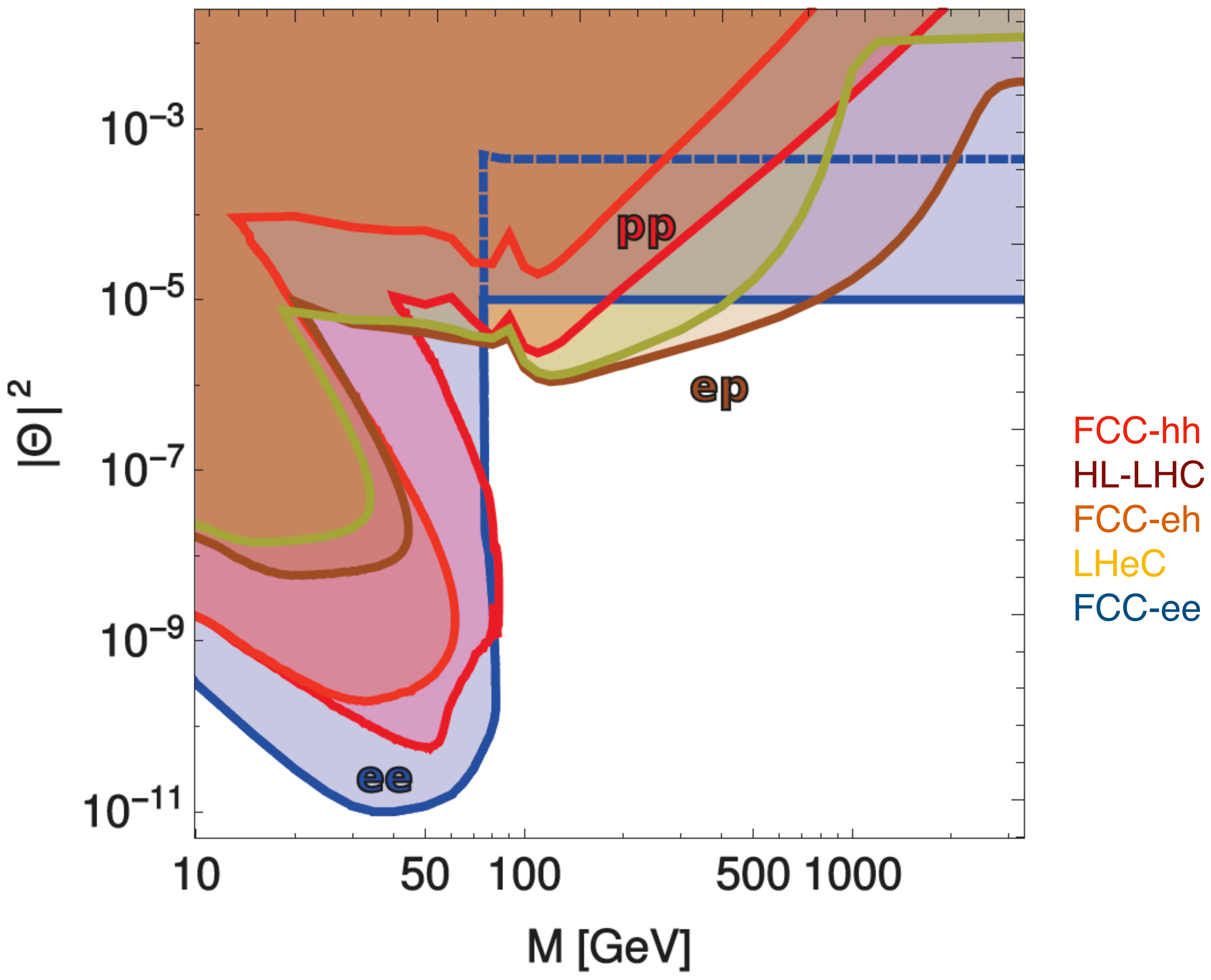
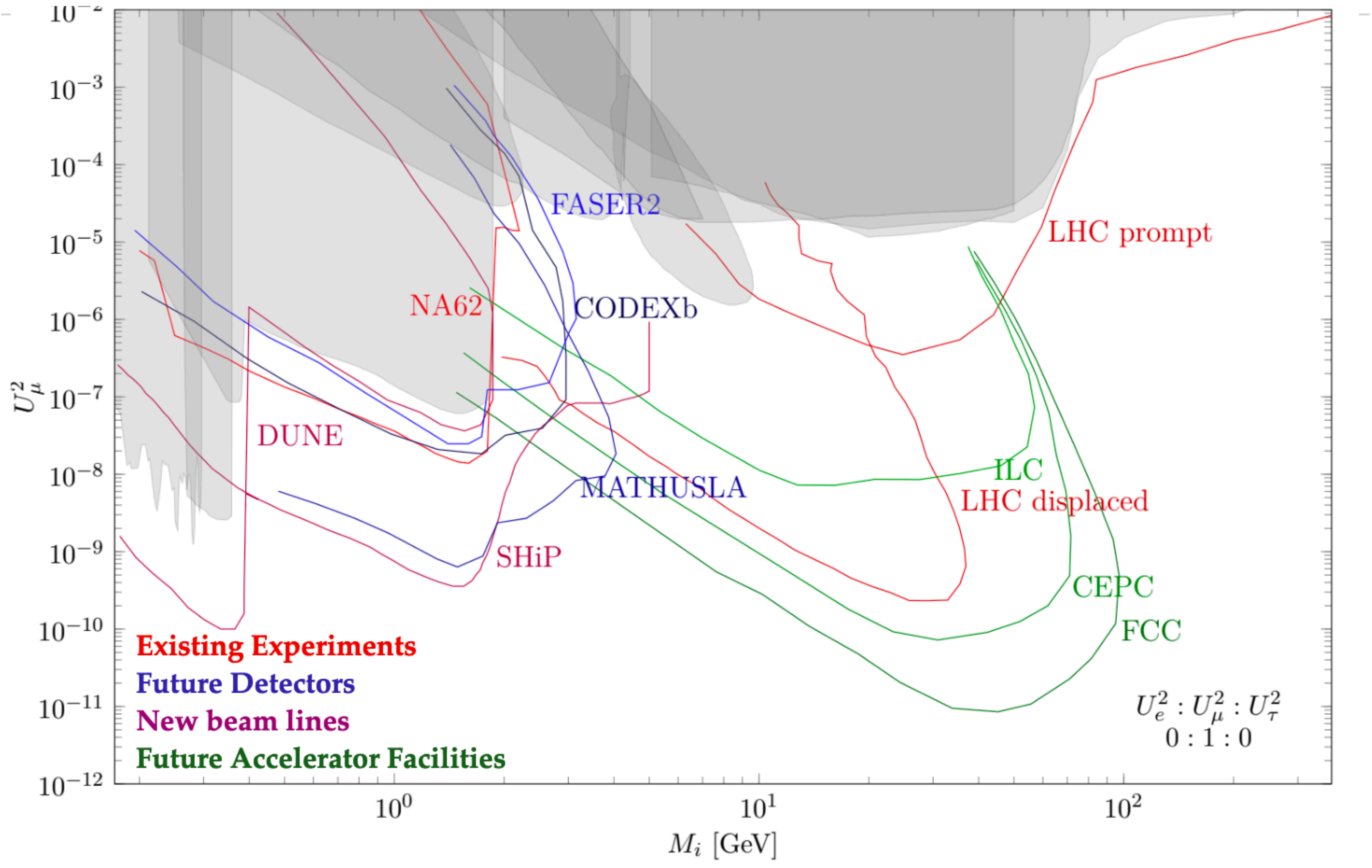
An e+e- circular collider could be fantastic for LLPs

arXiv:1612.02728

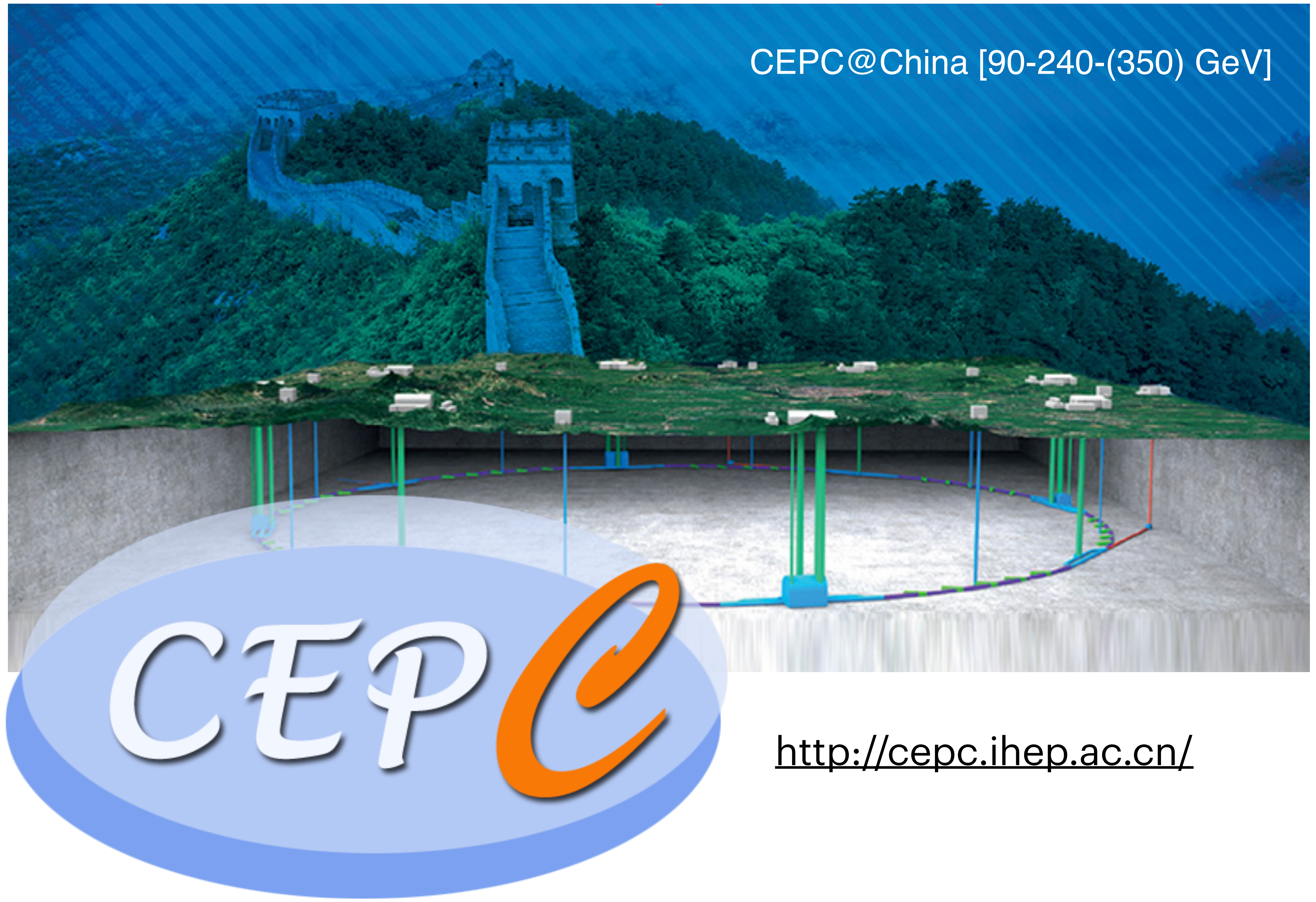


M. Drewes



And complementary to high-energy hadron machines for interesting physics cases

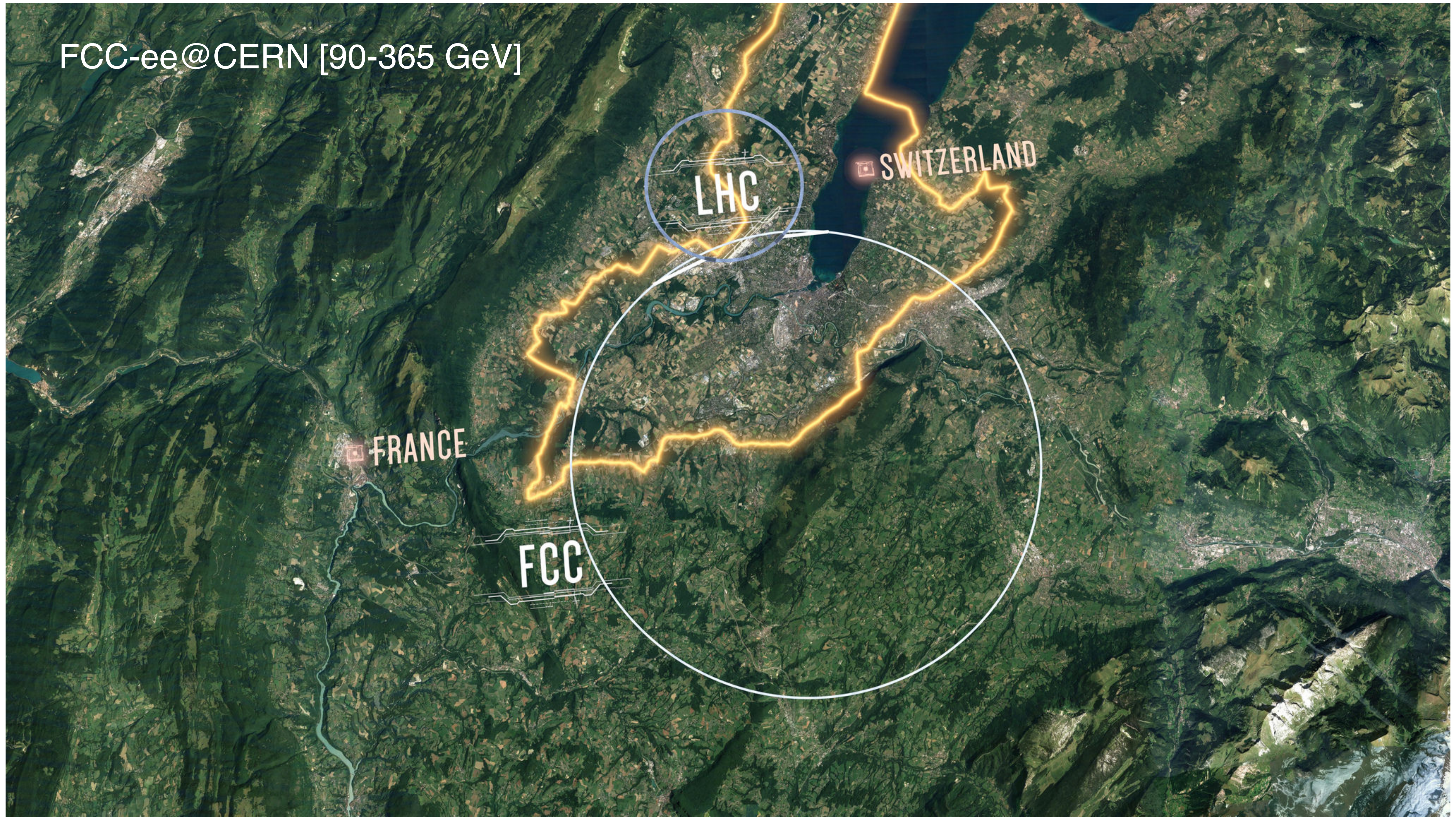
Circular e^+e^- Colliders



http://cepc.ihep.ac.cn/

FUTURE CIRCULAR COLLIDER

https://fcc-ee.web.cern.ch/



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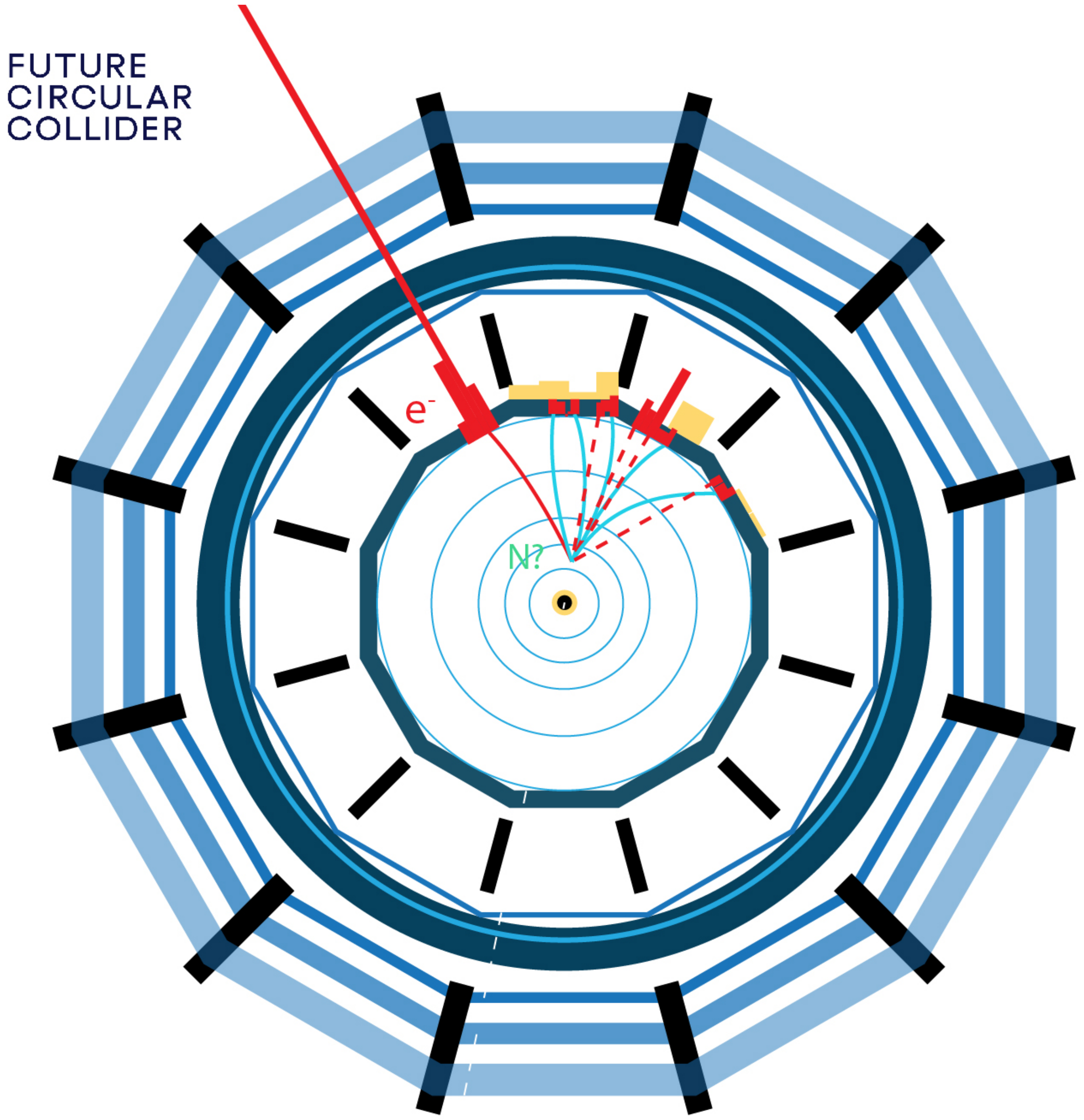
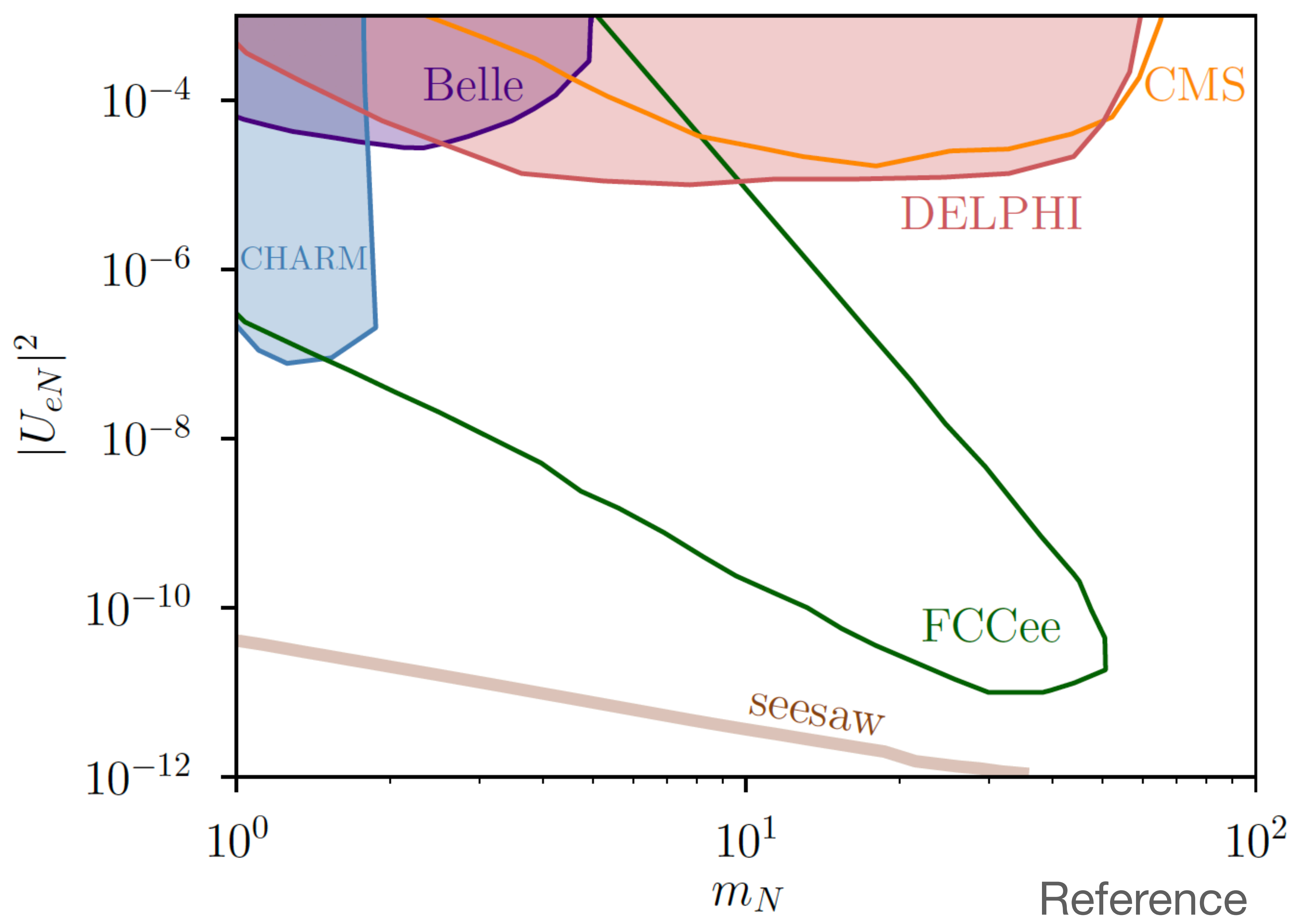
FCC-ee: Heavy Neutral Leptons

FUTURE CIRCULAR COLLIDER

- Many of the current HNL limits cover large neutrino mixing angles. For small values of the mixing angle, the decay length of the HNL can be significant → LLP signature (displaced vertex search)
- The FCC-ee will offer an unbeatable reach for HNL at the Z-Pole, making it the flagship of LLP searches in this collider





Reference

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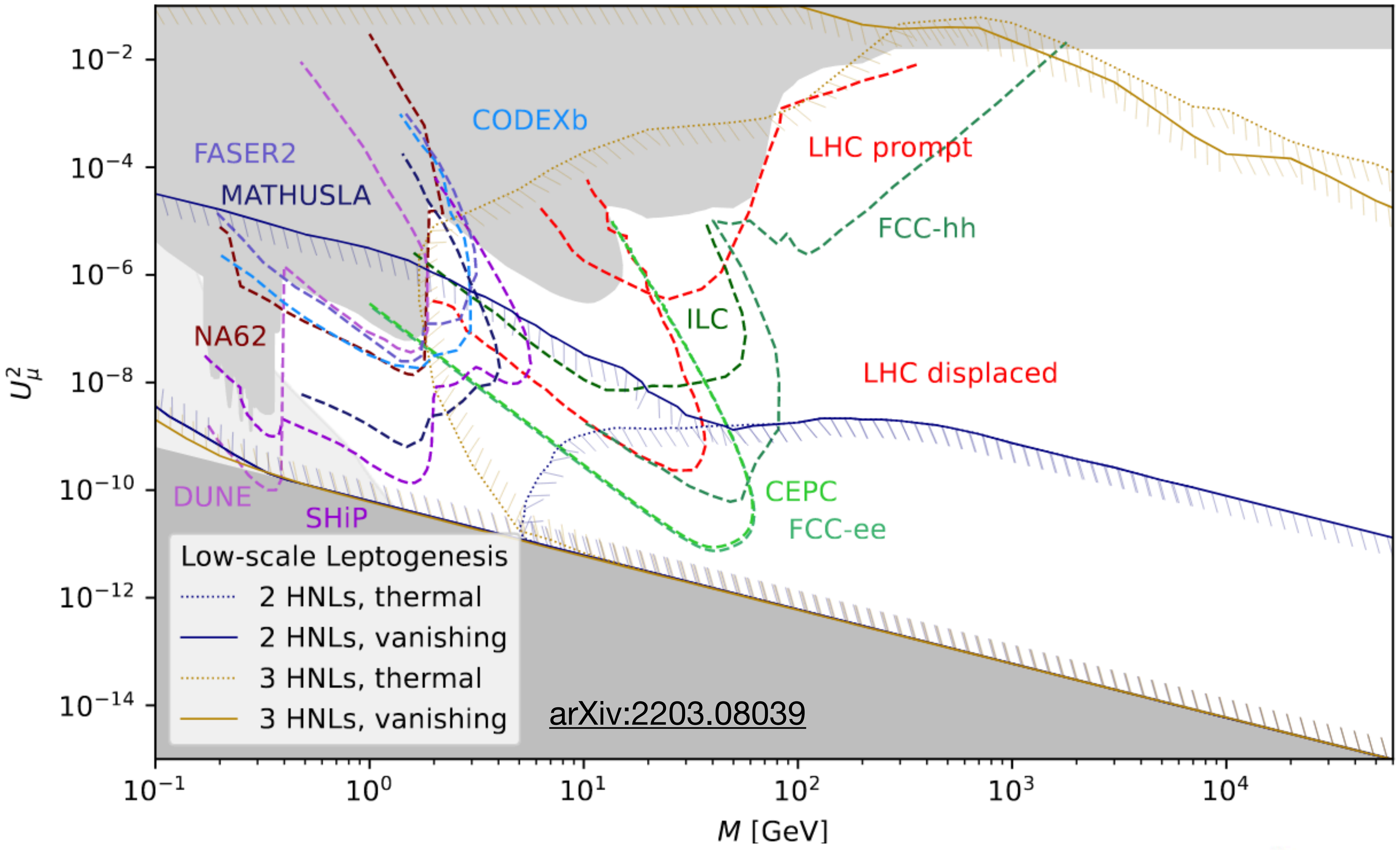
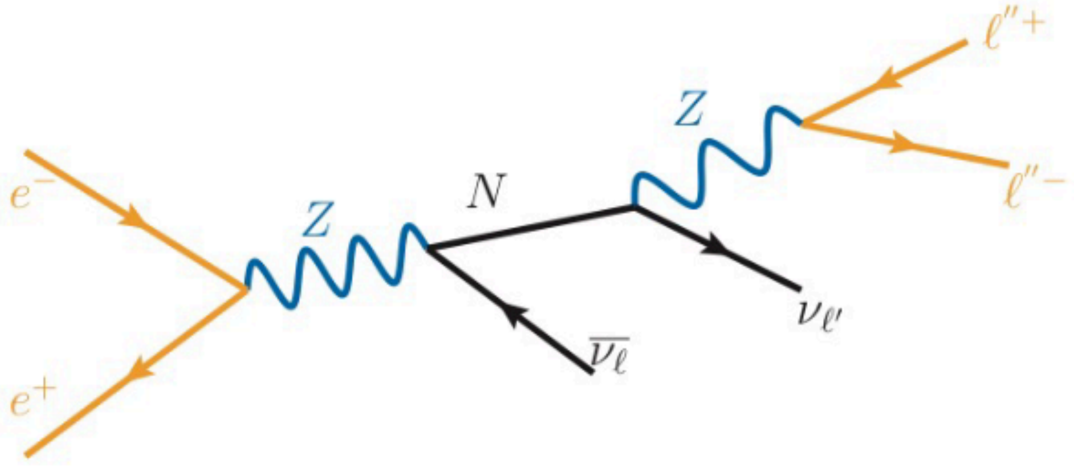
Experimental sensitivity studies

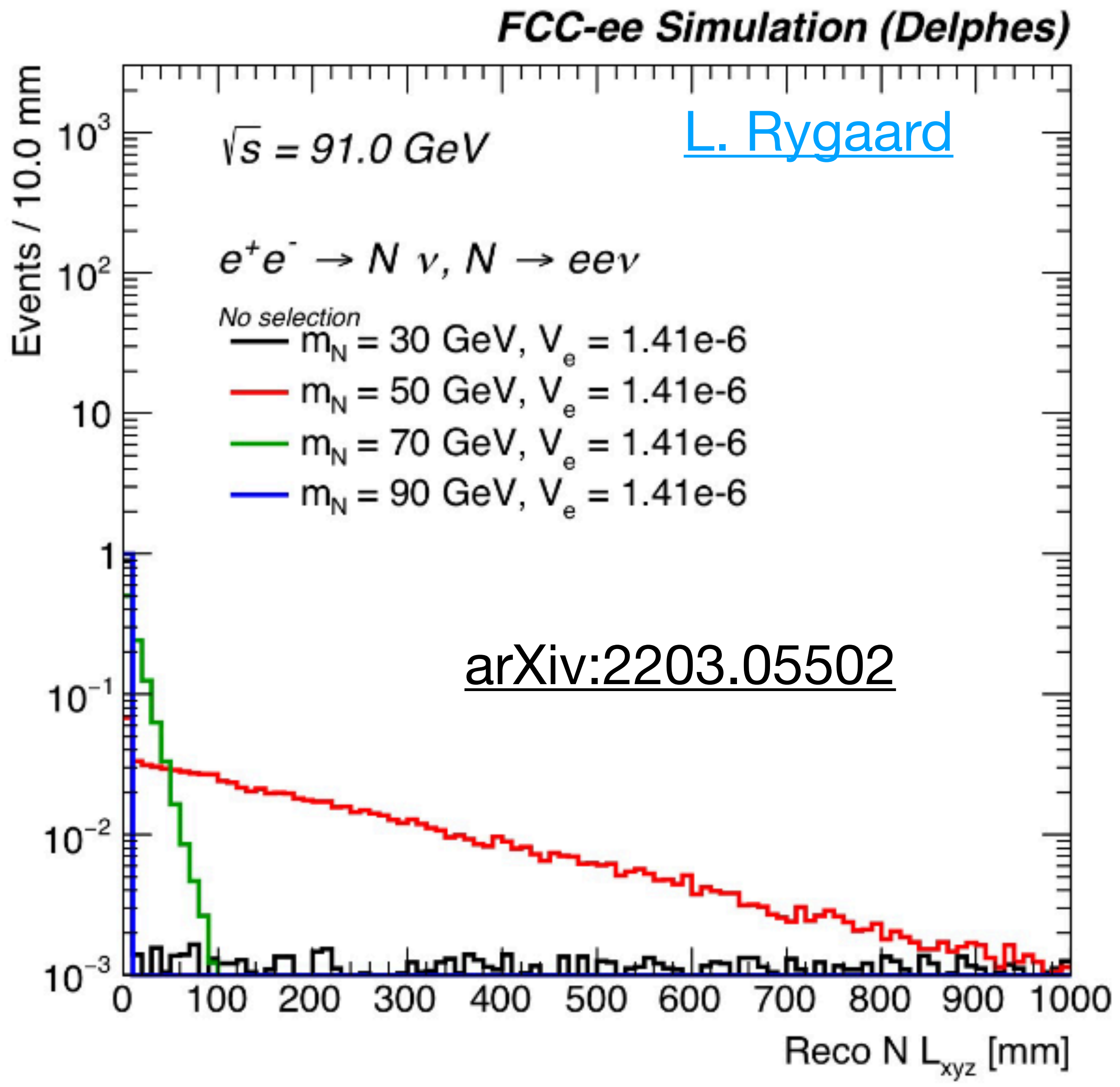


- Work in progress towards a complete sensitivity analysis implemented in FCC software
- First steps in eev final state (other final states to be added)
- Majorana/Dirac nature also studied (T. Sharma)

Master theses: Sissel Bay Nielsen, Rohini Sengupta, Lovisa Rygaard, Tanishq Sharma, Dimitri Moulin



Reconstruction-level three-dimensional decay length of the N



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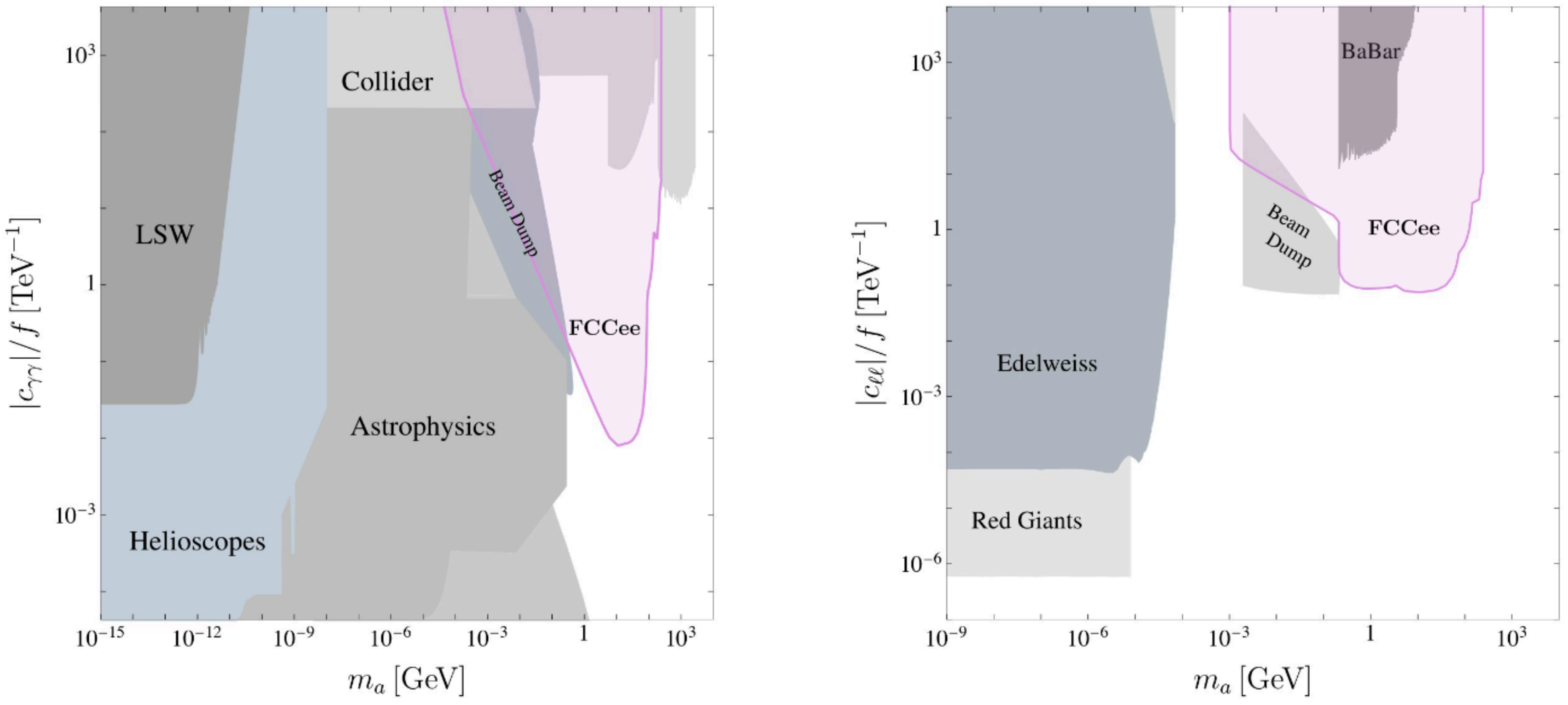
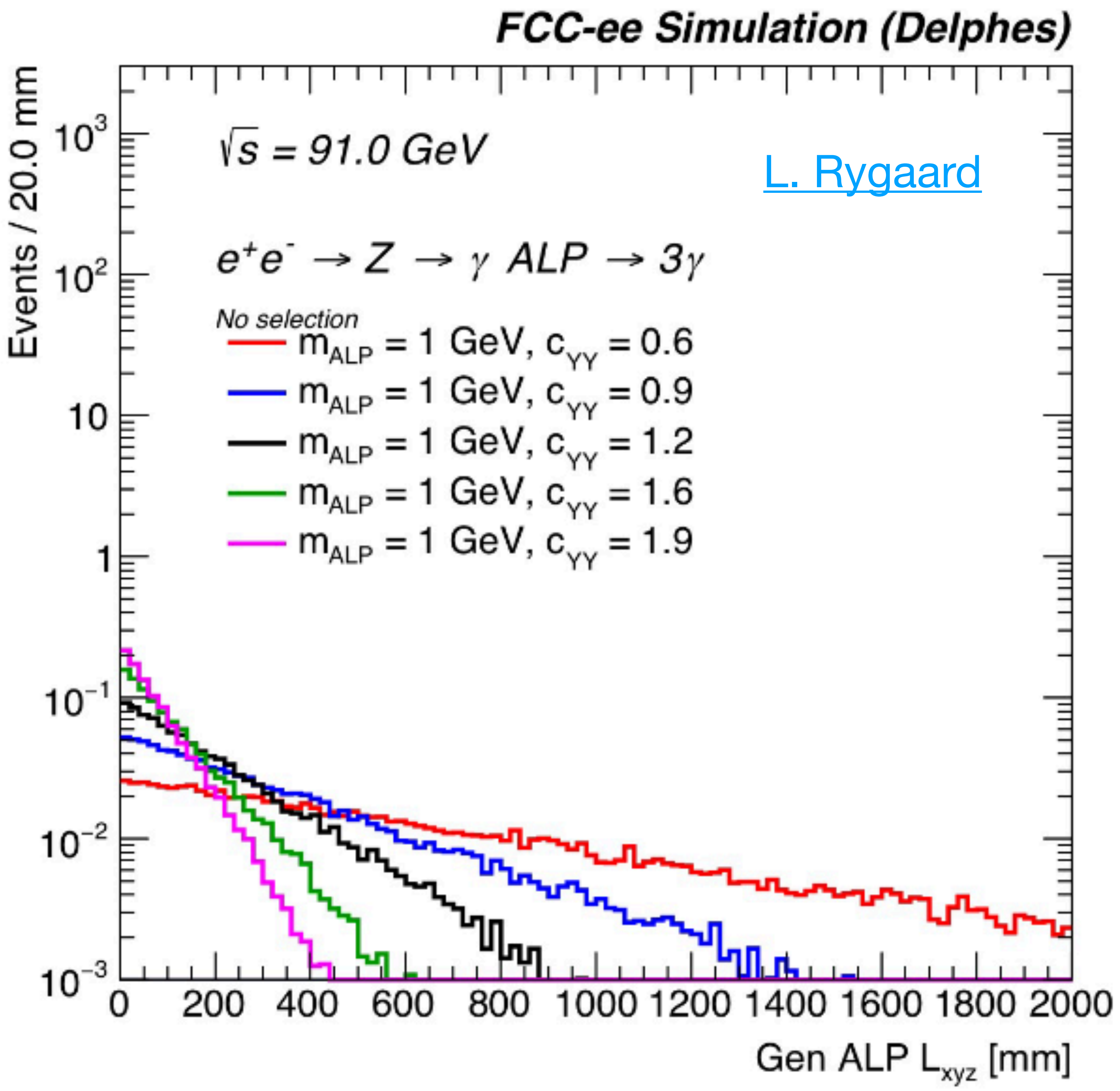
arXiv:2203.05502

FCC-ee: ALPs

- Specially sensitive final states at the FCC-ee of ALPs produced with photons
  - Calorimetry crucial to study this signature
- First generation studies with FCC software available



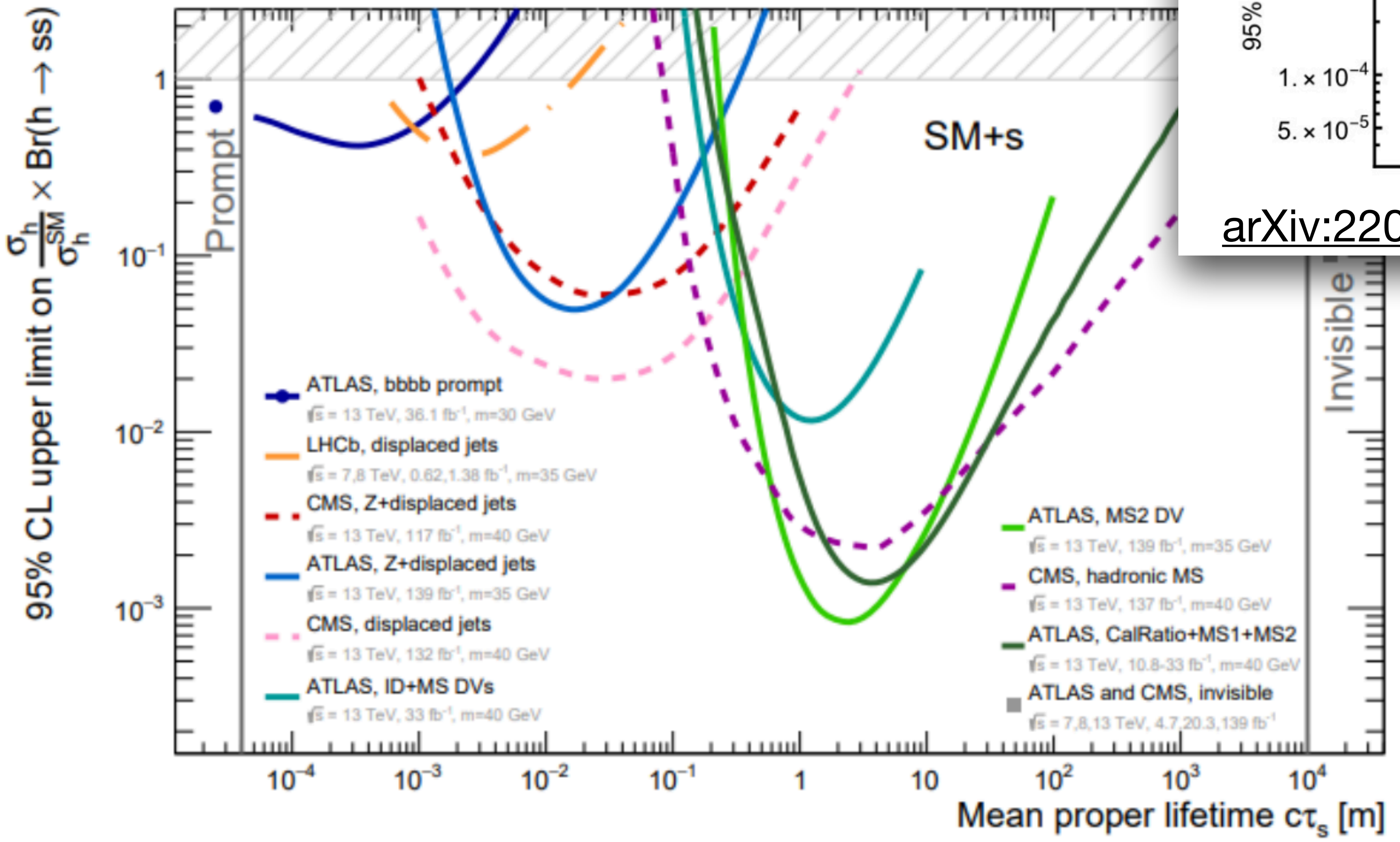


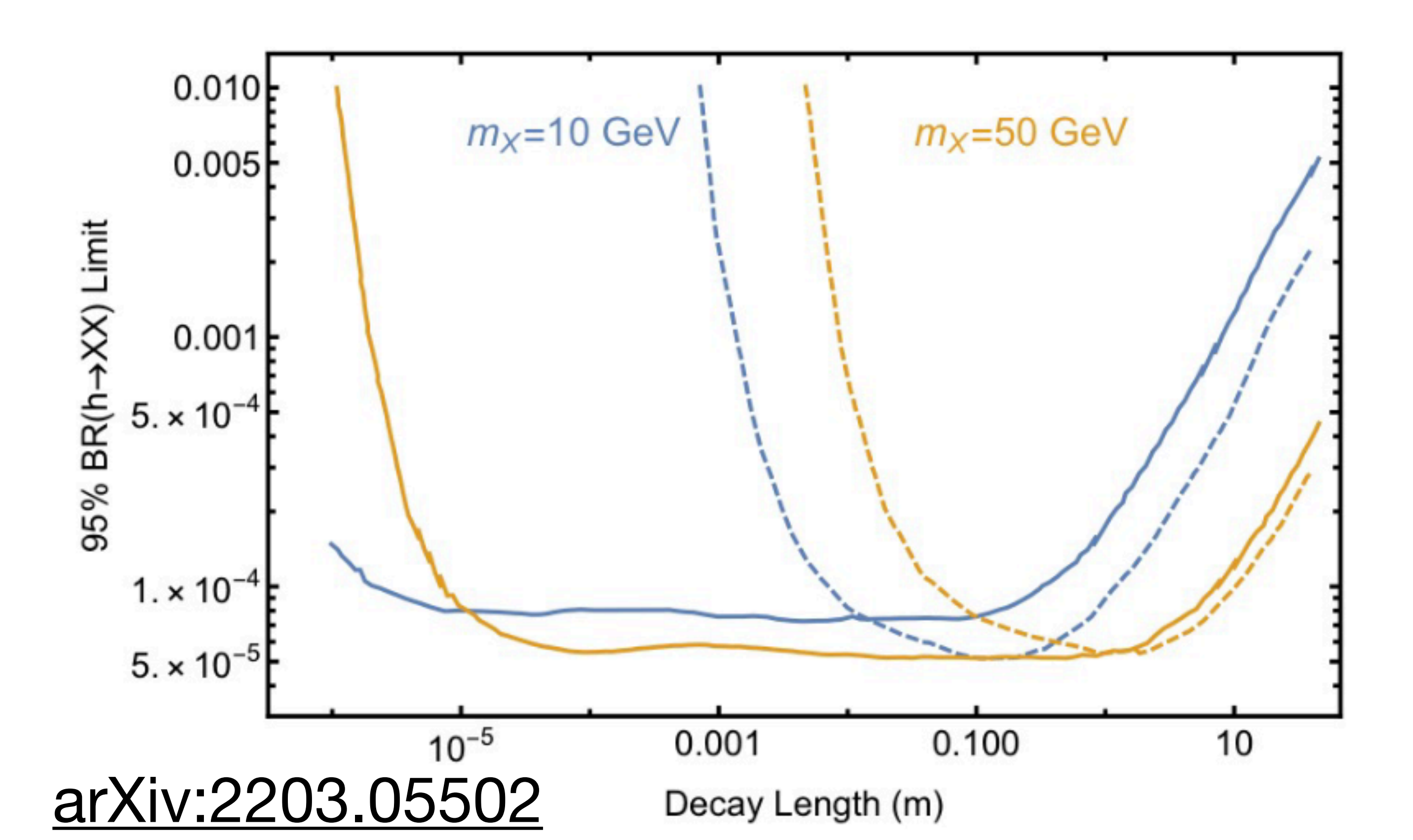
Truth-level decay length of the ALP

FCC-ee: Exotic Higgs boson decays

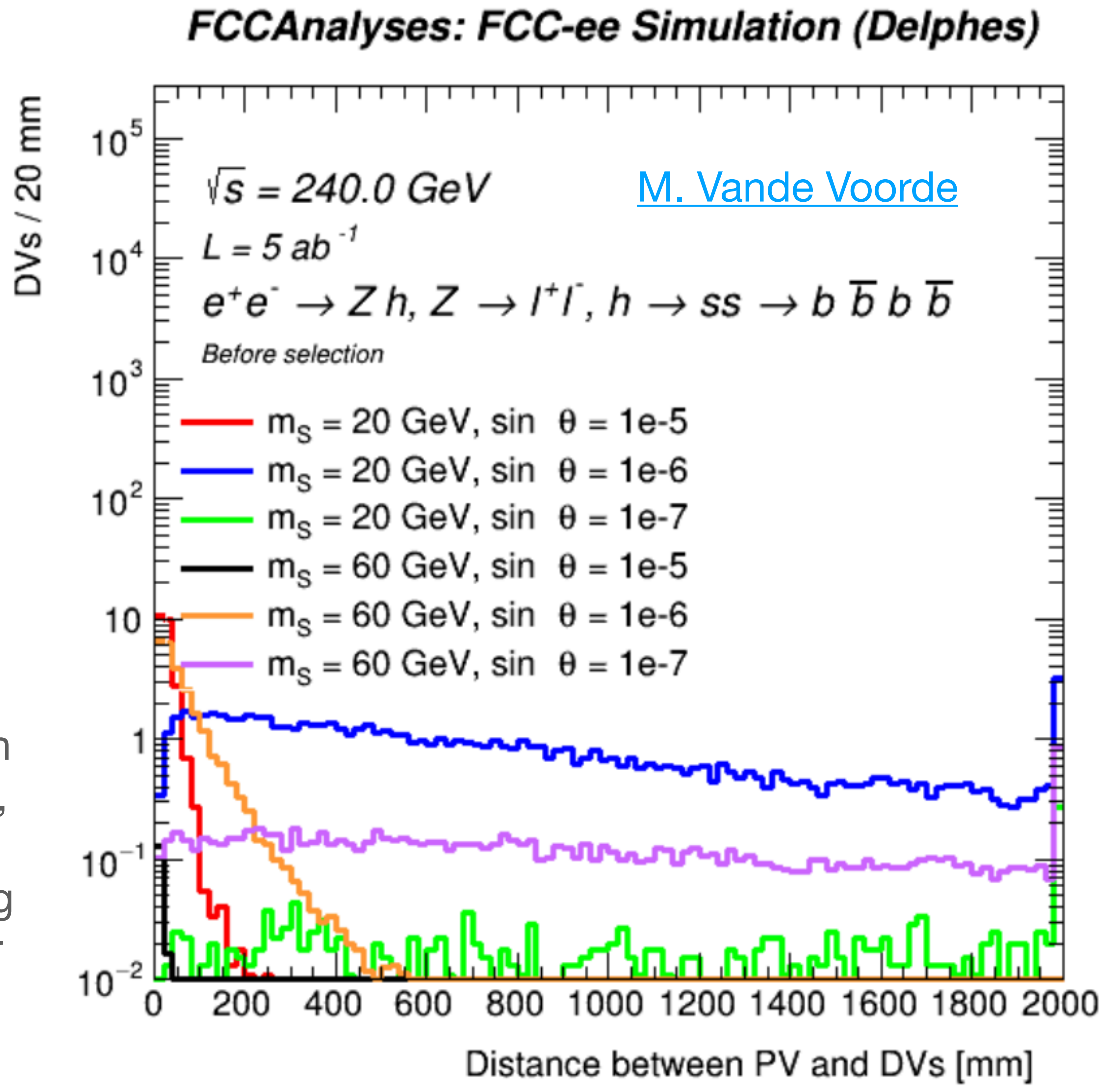
- Exotic Higgs decays to long-lived particles (LLPs) are possible and present in many models:
  - SM extensions with scalars/fermions/ vectors, MSSM, NMSSM, Hidden Valleys, Twin Higgs (arXiv:1312.4992, arXiv:1812.05588, arXiv:1712.07135)

arXiv:2111.12751



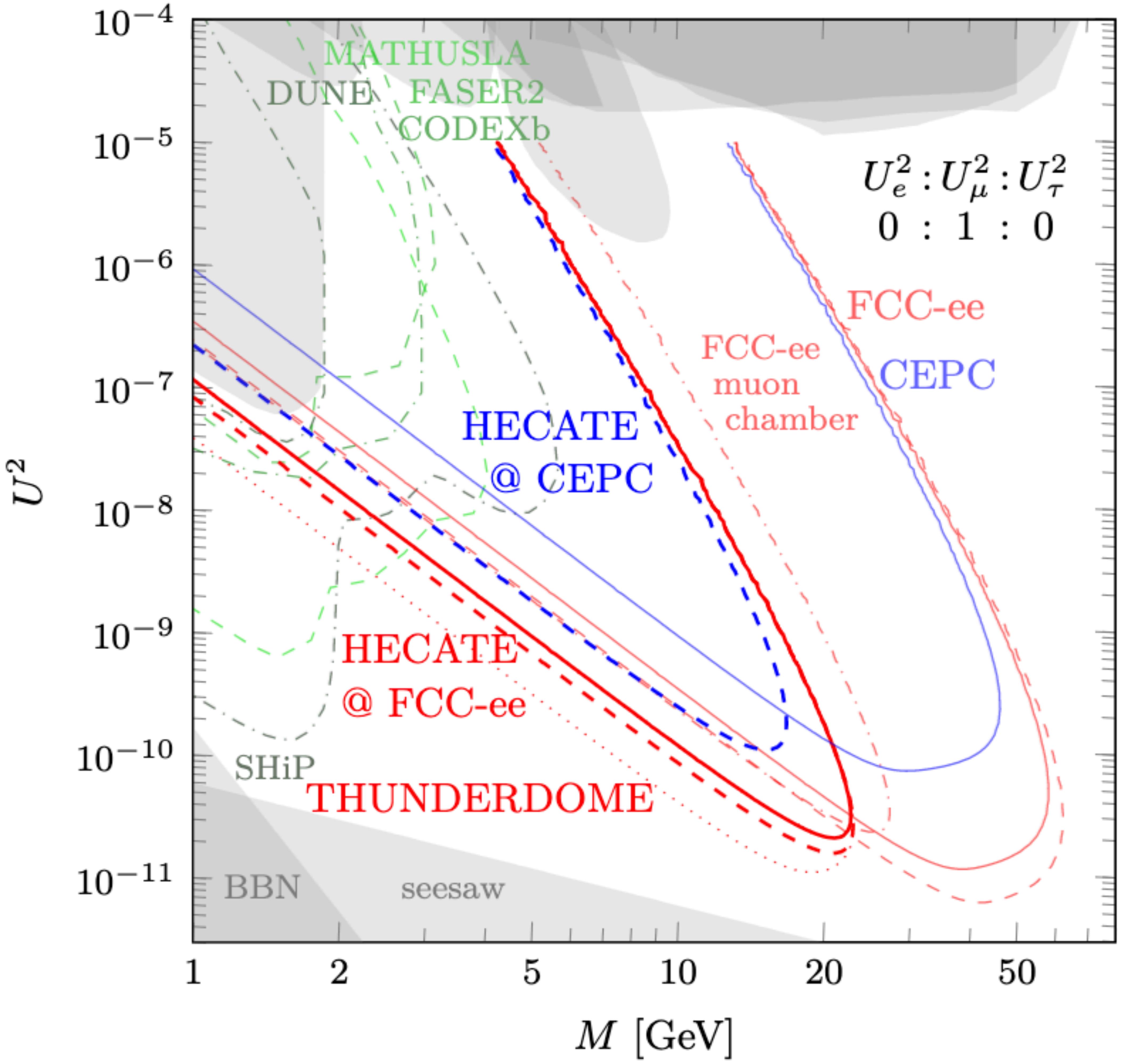


arXiv:2203.05502



Experimental studies ongoing with a SM + S model (arXiv:1312.4992, arXiv:1412.0018) Long-lived scalars for sufficiently small mixing between the Higgs and the scalar

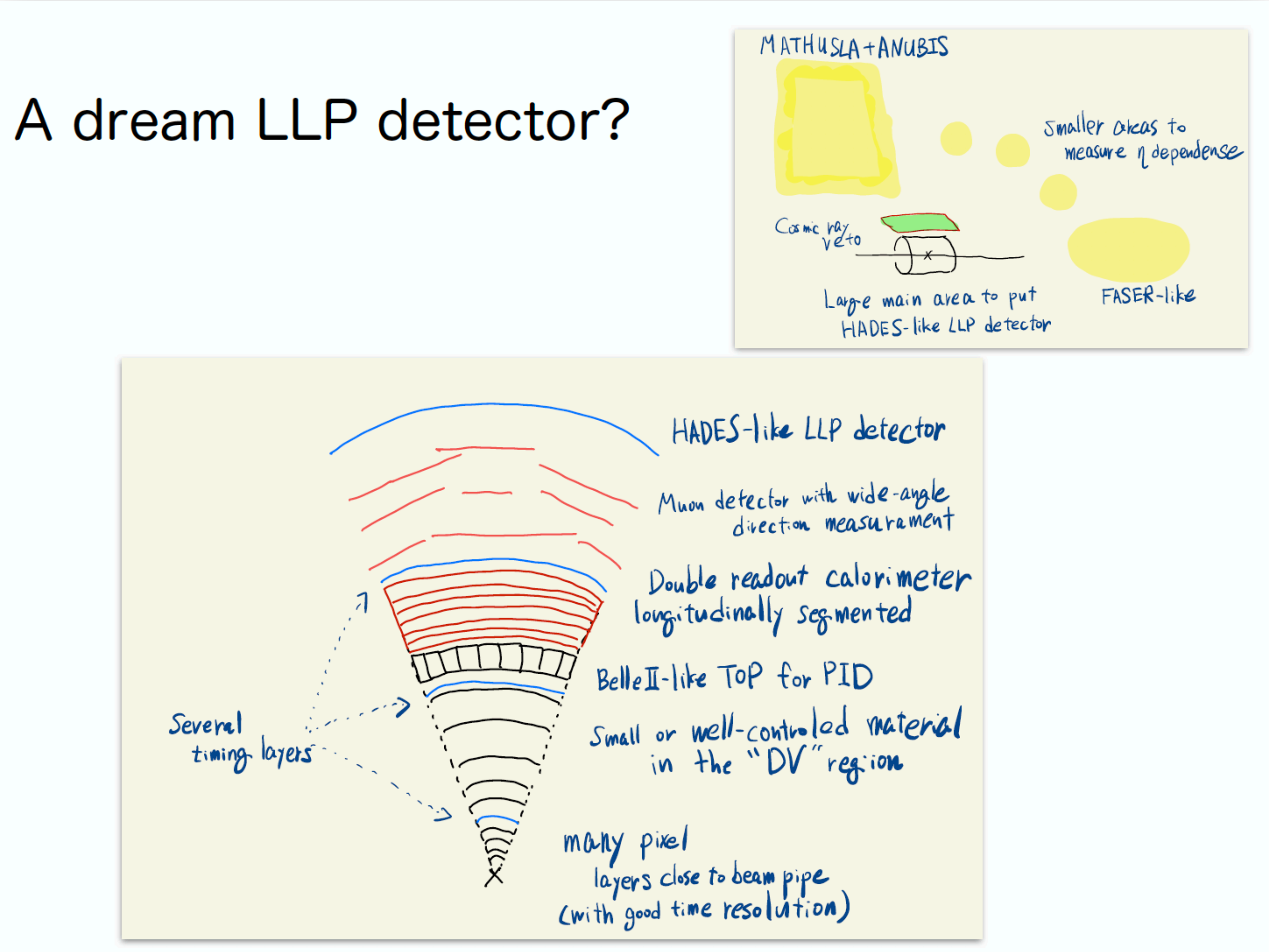
Extra detectors!



- Following the plans for different additional LLP experiments at the HL-LHC it is possible to also envision similar concepts at other future colliders
- HECATE: A long lived particle detector concept for the FCC-ee or CEPC: arXiv:2011.01005
- The civil engineering of the FCC-ee will have much bigger detector caverns than needed for a lepton collider (to use them further for a future hadron collider)
- We could install extra instrumentation at the cavern walls to search for new long lived particles

FAr Detectors
arXiv:1911.06576
for ALPs at FCC-ee, CepC
arXiv:2201.08960

One thing is clear



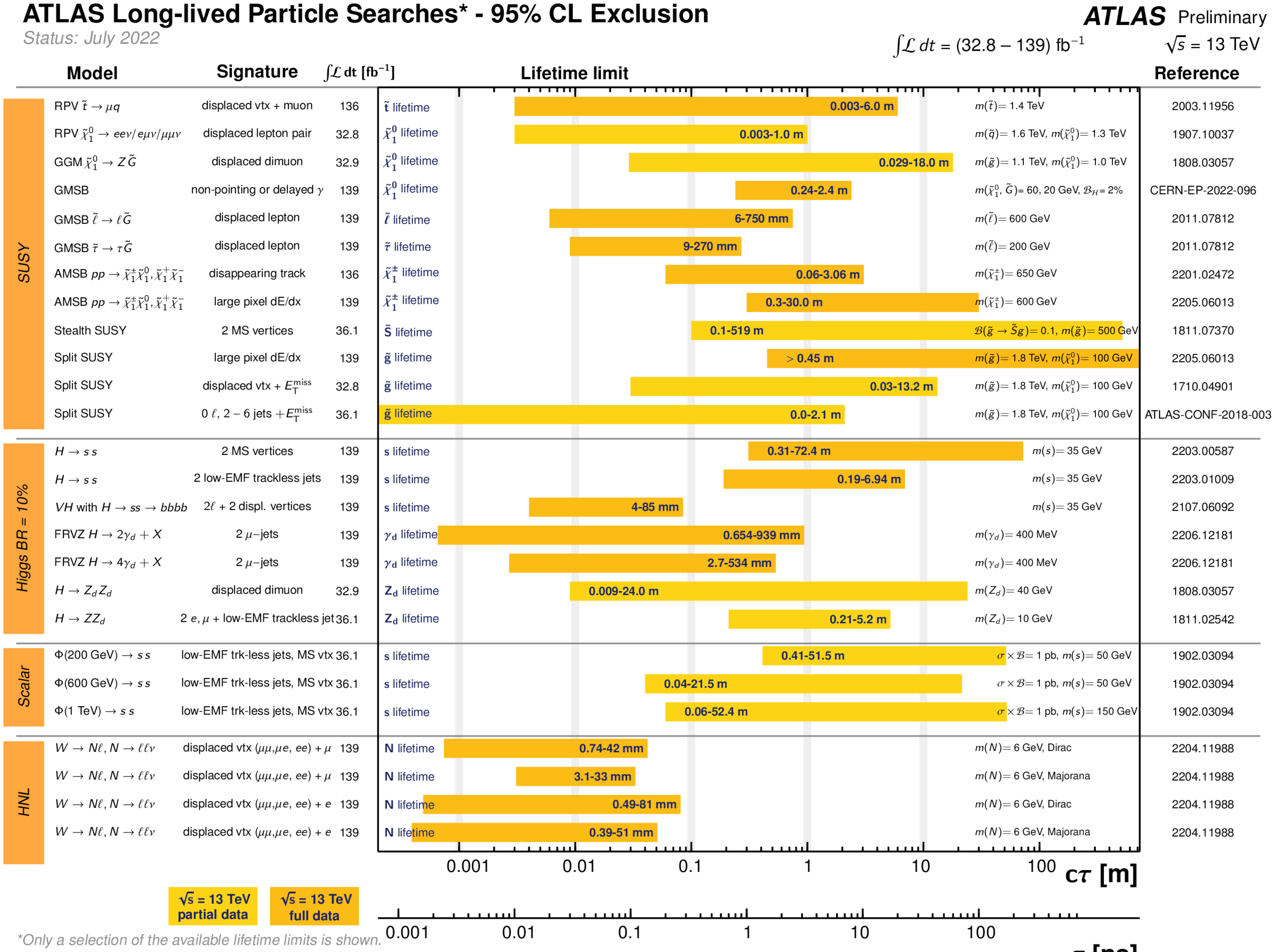
It is a good time to plan our ***dream LLP detectors***, following Ryu Sawada first example at the LLP workshop in November 2020 (link)

- No matter what we build, LLP challenges will be common (caveats: trigger much more crucial in hadron machines, muon colliders coming with their own special challenges)
- At this point we have two ways to go:
  - Design the future detectors as usual and then try to make the best out of them for LLPs
    - which can be done but won't be easy as we know from the experience at the LHC -and before-
  - Design the future detectors with LLP in mind, prioritising for example displaced tracking and timing, and budgeting for unexpected signals

In Summary

- Searches for long-lived particles offer a powerful, signature-driven alternative and complement to mainstream searches for new physics at colliders
    - Connected to very interesting physics questions, such as neutrino masses, and central to hidden sectors that could explain dark matter
    - They probe challenging, non-standard experimental signatures that defy reconstruction and identification techniques at collider experiments
    - **The perfect environment for creativity: in both methods and experimental setup**
- A variety of additional experiments ongoing and proposed to complement the LHC experiments at collision points, or using beam dumps, at the LHC and beyond
- In future lepton colliders, precision machines built to stress-test the Higgs sector, long-lived signatures could hold the key to new physics: HNLs, ALPs, exotic decays of the Higgs boson
    - **Opportunity to plan the future facilities with LLPs in mind!**

Backup



Latest Briefing: https://atlas.cern/updates/briefing/search-long-lived-particles

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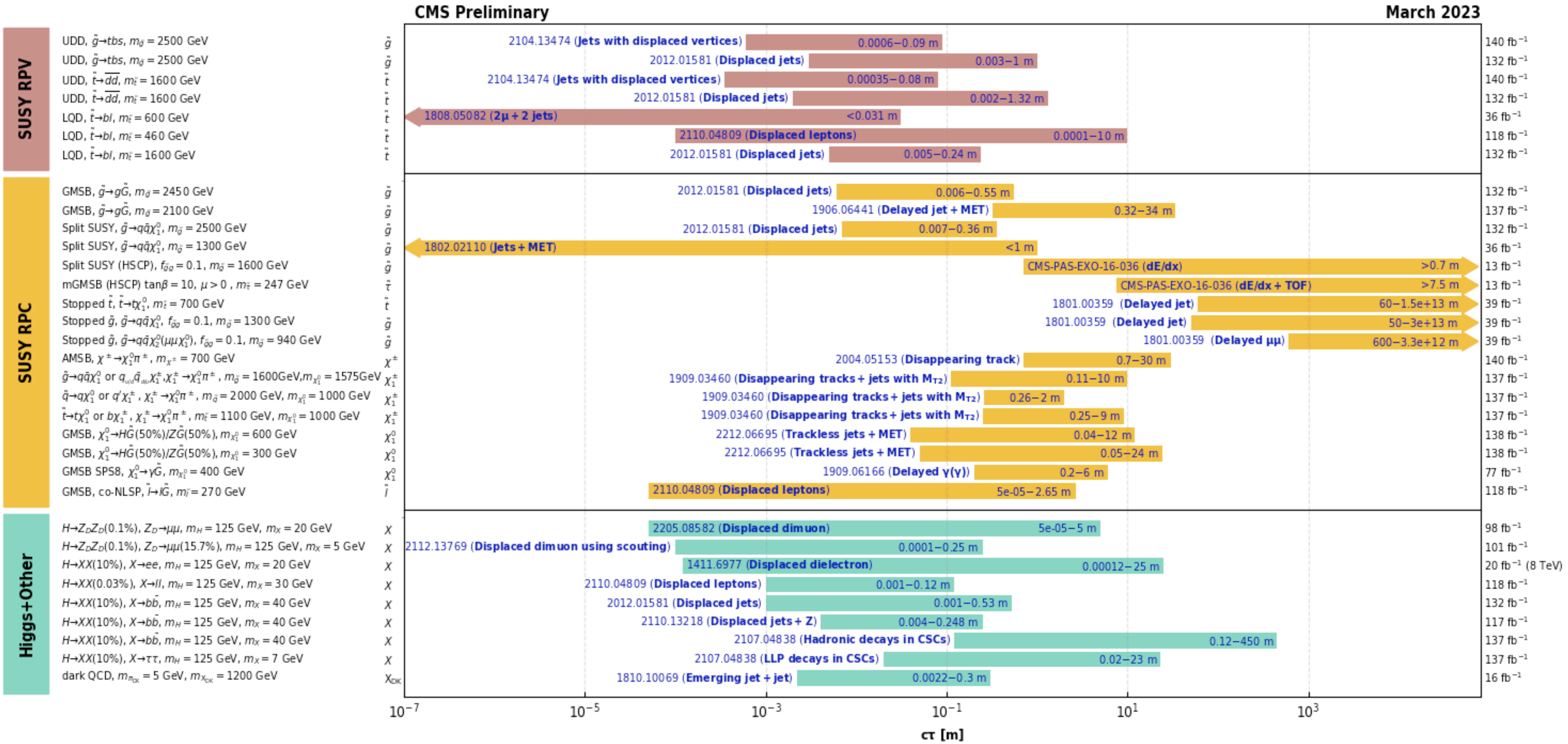
Overview of CMS long-lived particle searches



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.

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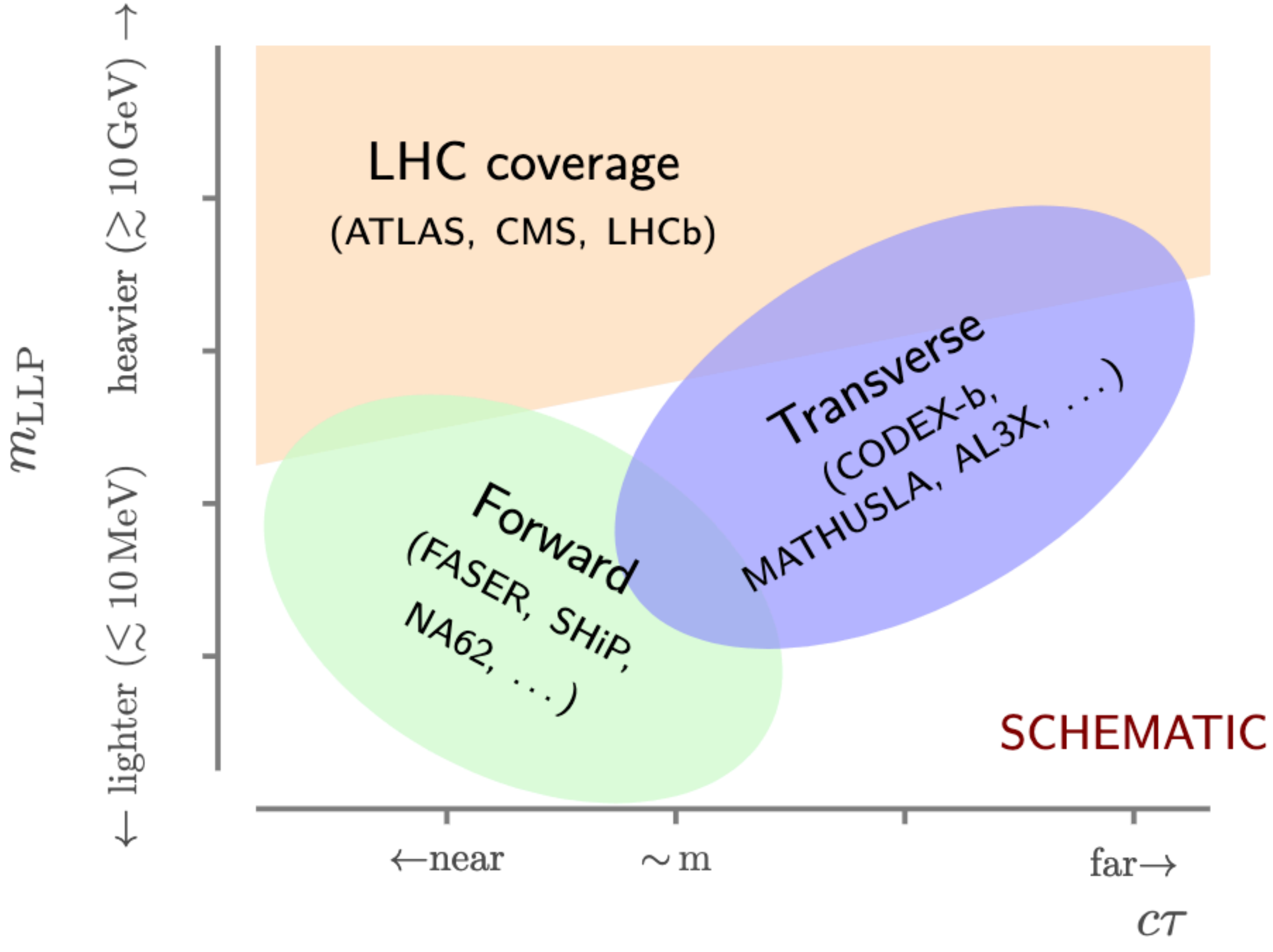
Forward

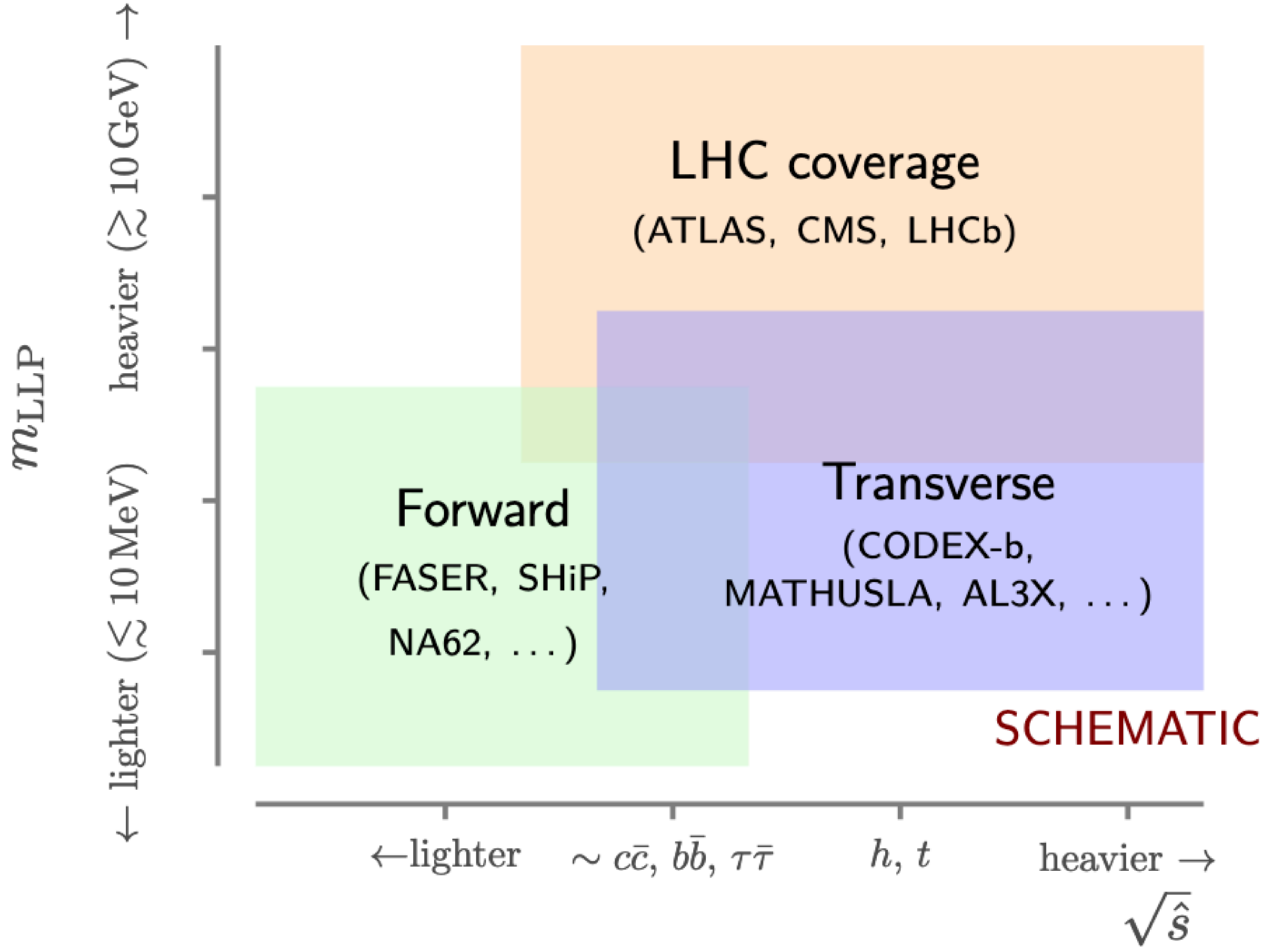
- Forward detectors give access to light, weakly-interacting particles with significant lifetime
  - Even small, inexpensive detectors can have a strong, complementary physics case
  - Provide sensitivity to a wide range of BSM physics models (dark γ, ALPS, HNL, light DM, mCP etc)
  - Probing uncovered regions of phase space, even with 2022 data already in some cases
- Three new detectors (FASER, SND@LHC, MoEDAL-MAPP) making great progress
  - First physics already there!
- Longer term, proposal for dedicated forward physics facility to take advantage of HL-LHC
  - Would give a rich and broad physics programme
  - Tight timeline so please contribute to studies if interested

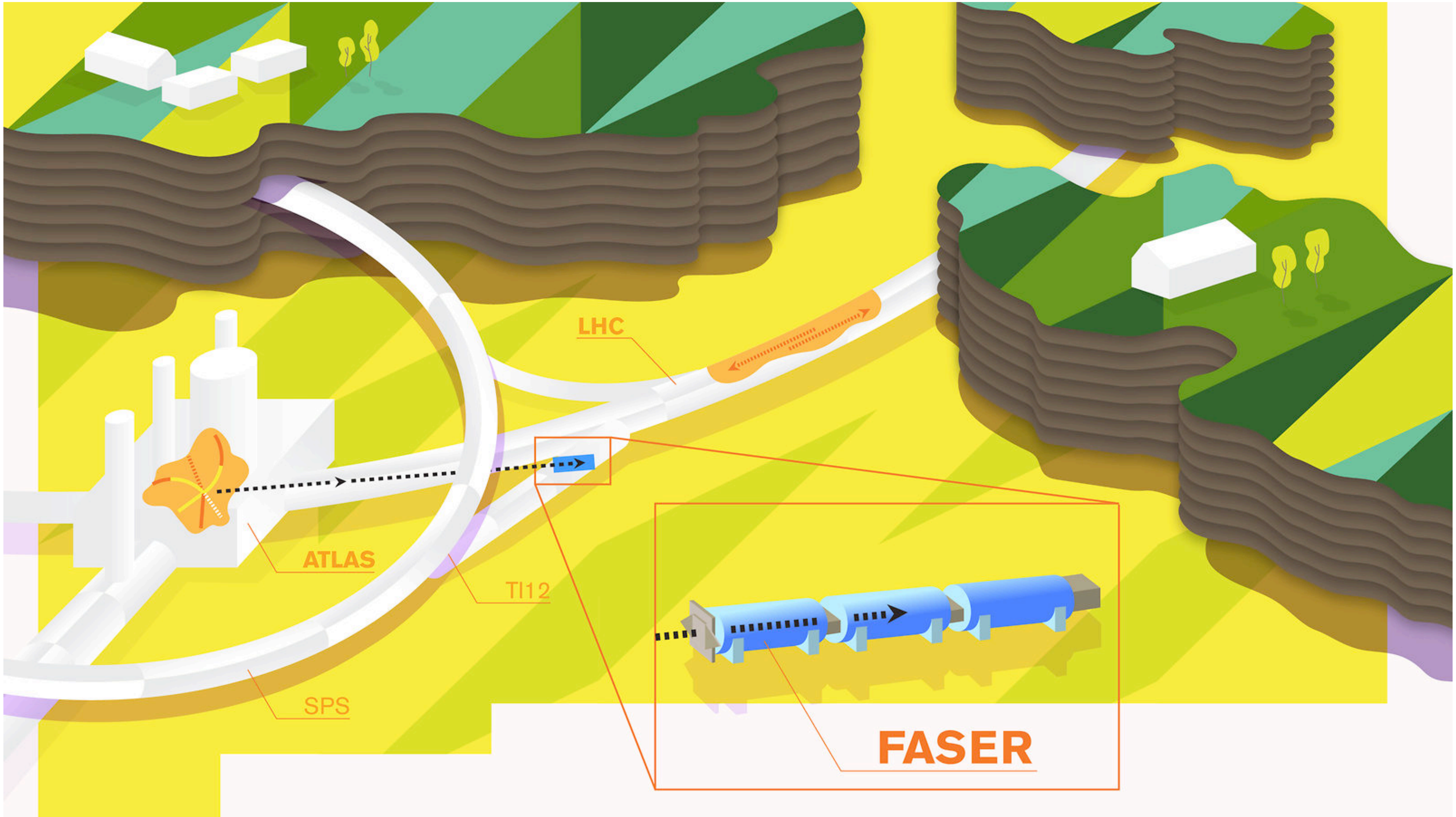
Transverse

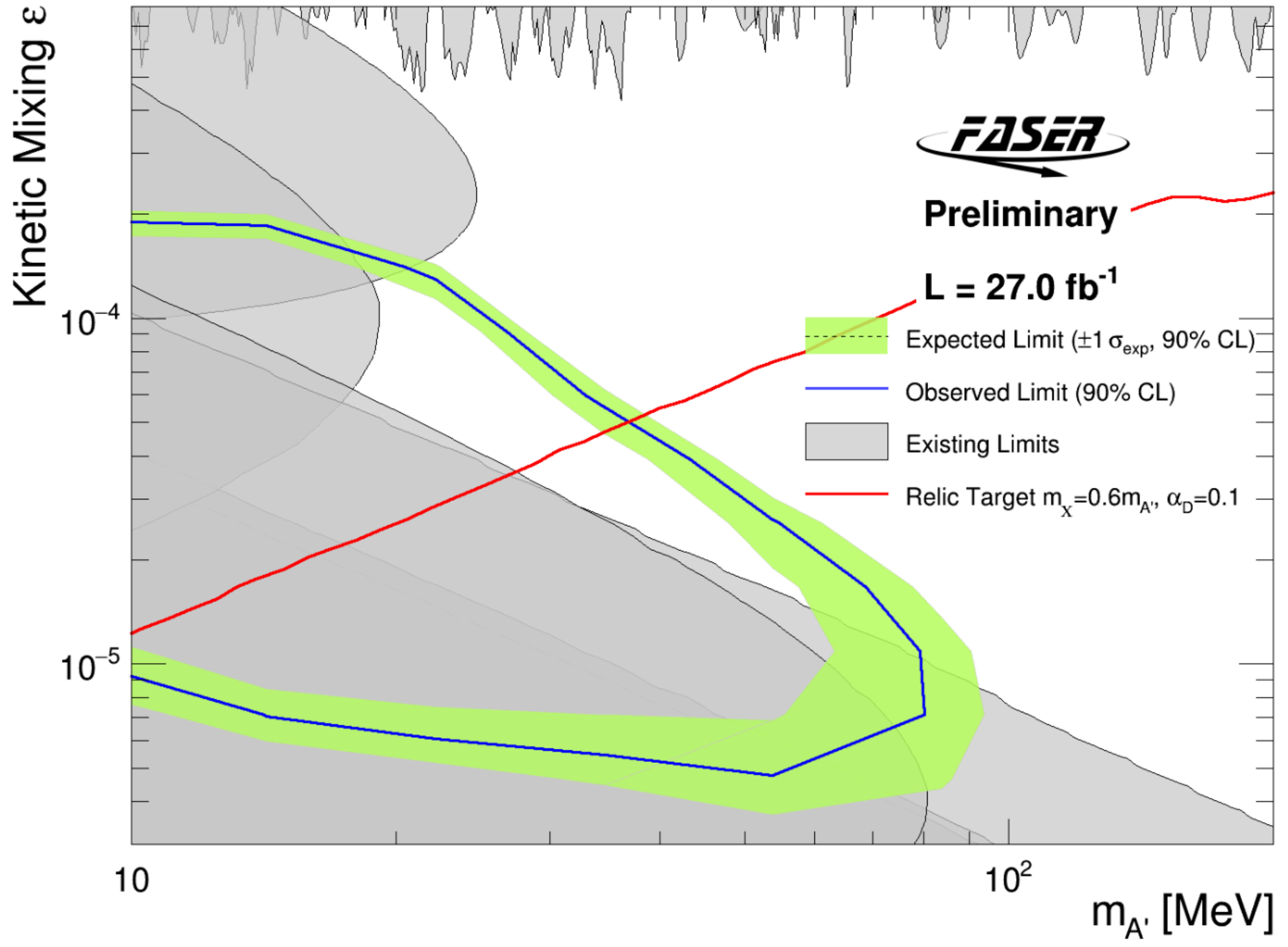
- Transverse experiments:
  - Search for decays of heavier particles: heavy mediators, eg. Higgs
- Dedicated transverse LLP are a relatively cheap way to explore a large region of the parameter space
  - Complementarity among different detectors (also forward)

Complementarity






LHC
ATLAS
TI12
SPS
FASER



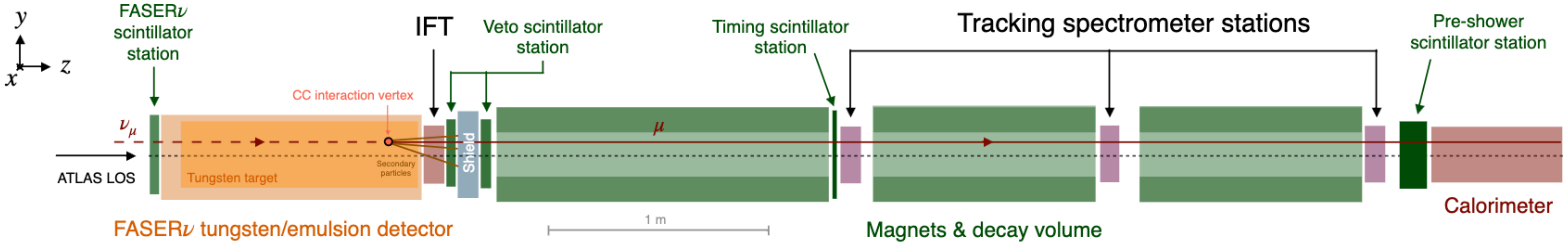
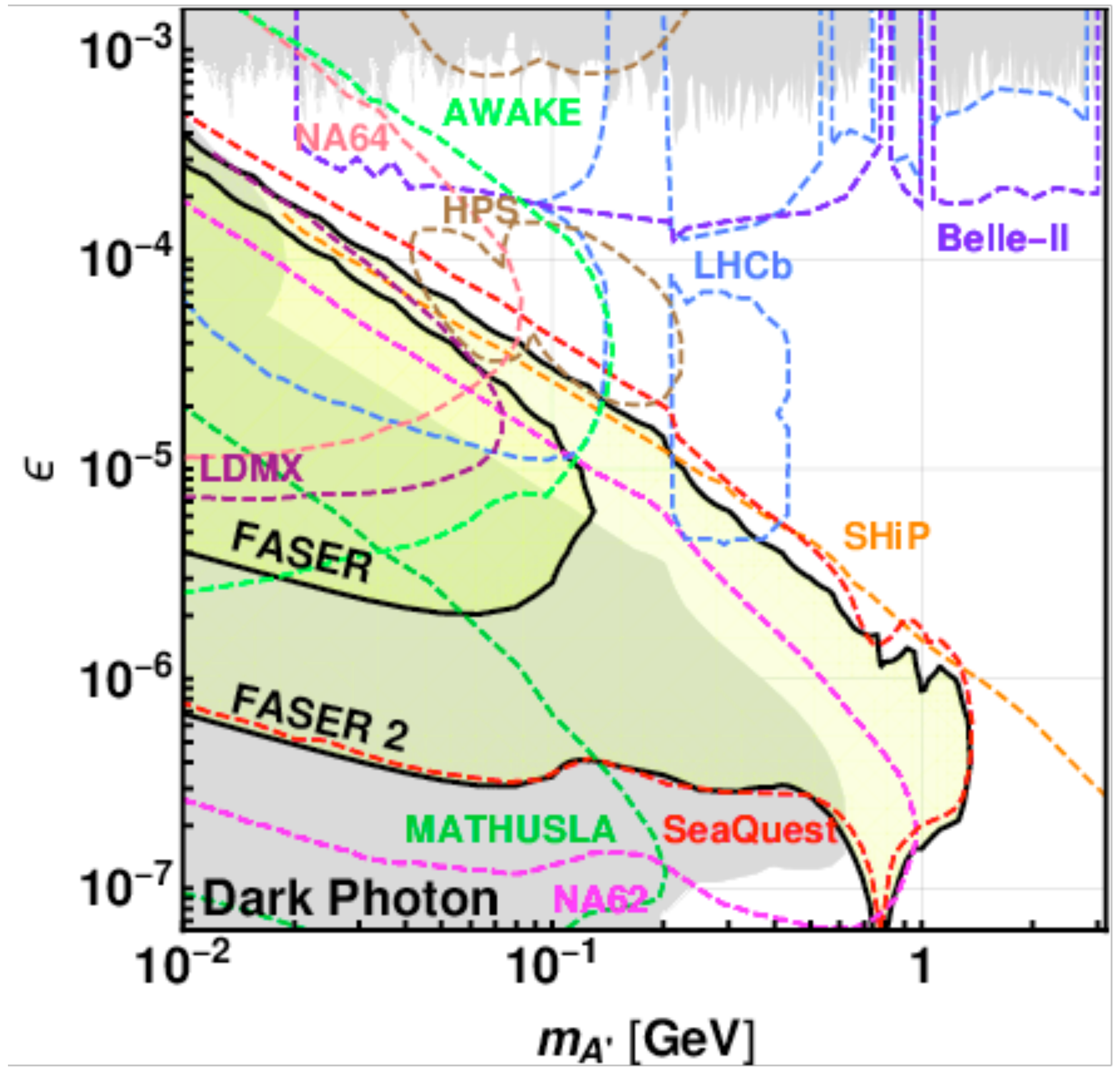
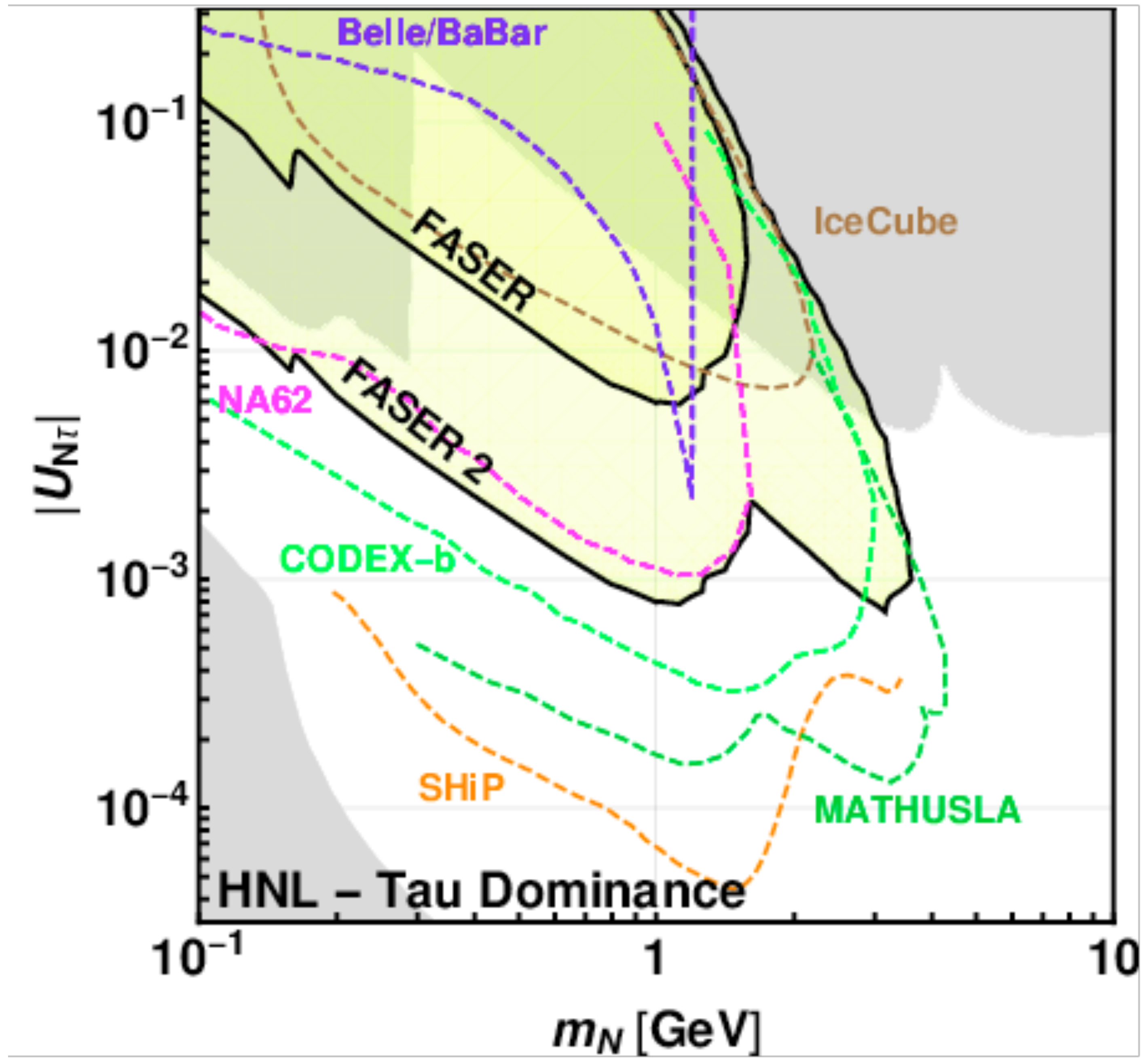
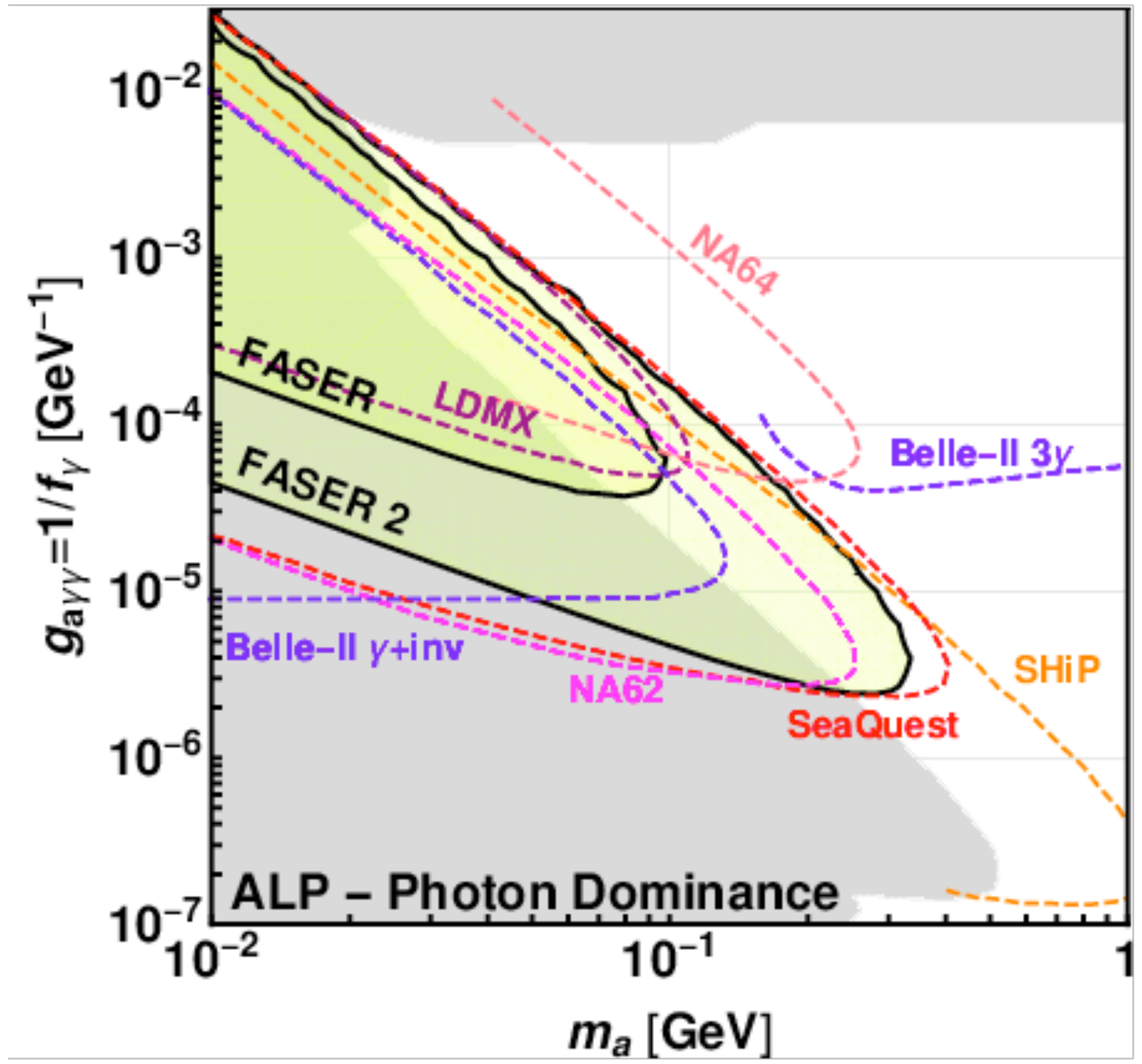


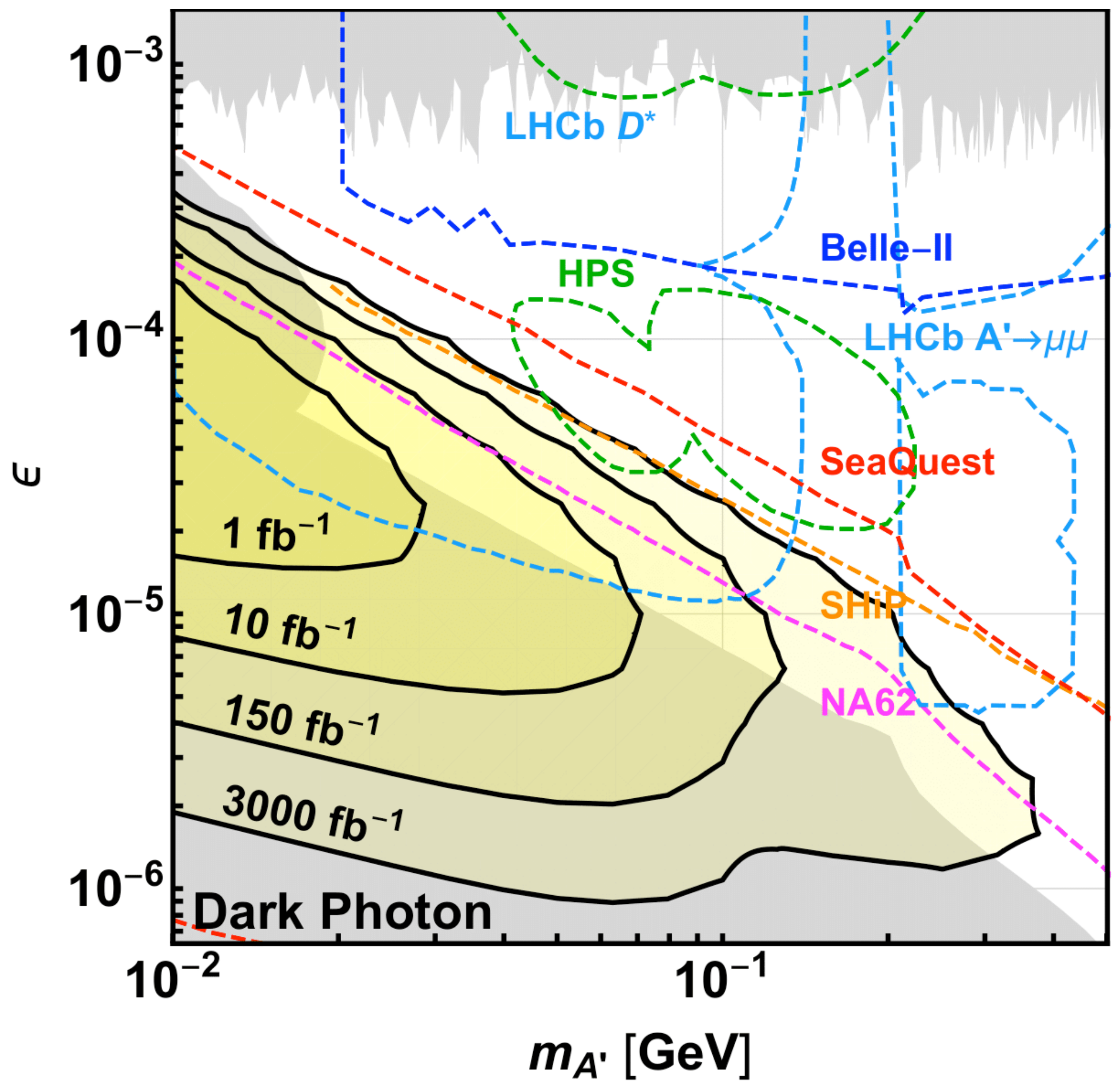
FIG. 1. Schematic side view of the FASER detector with a muon neutrino undergoing a CC interaction in the emulsion target.

FASERν: subdetector of FASER designed to study neutrino interactions at high energies along the beamline.



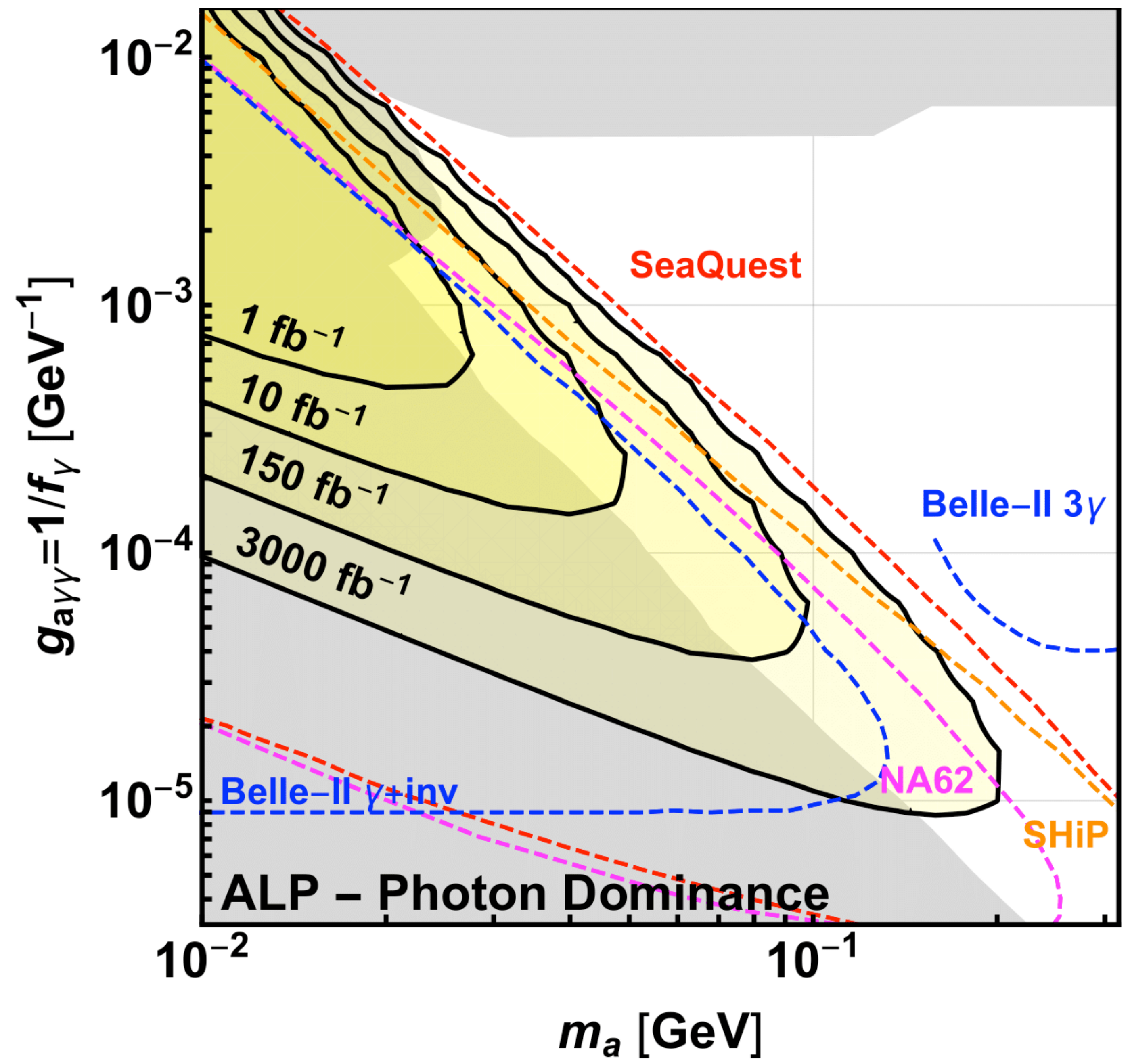






FASER:
radius R = 10 cm, length D = 1.5 m
luminosity L = 150 fb-1

FASER 2:
radius R = 1m, length D = 5 m
luminosity L = 3 ab-1



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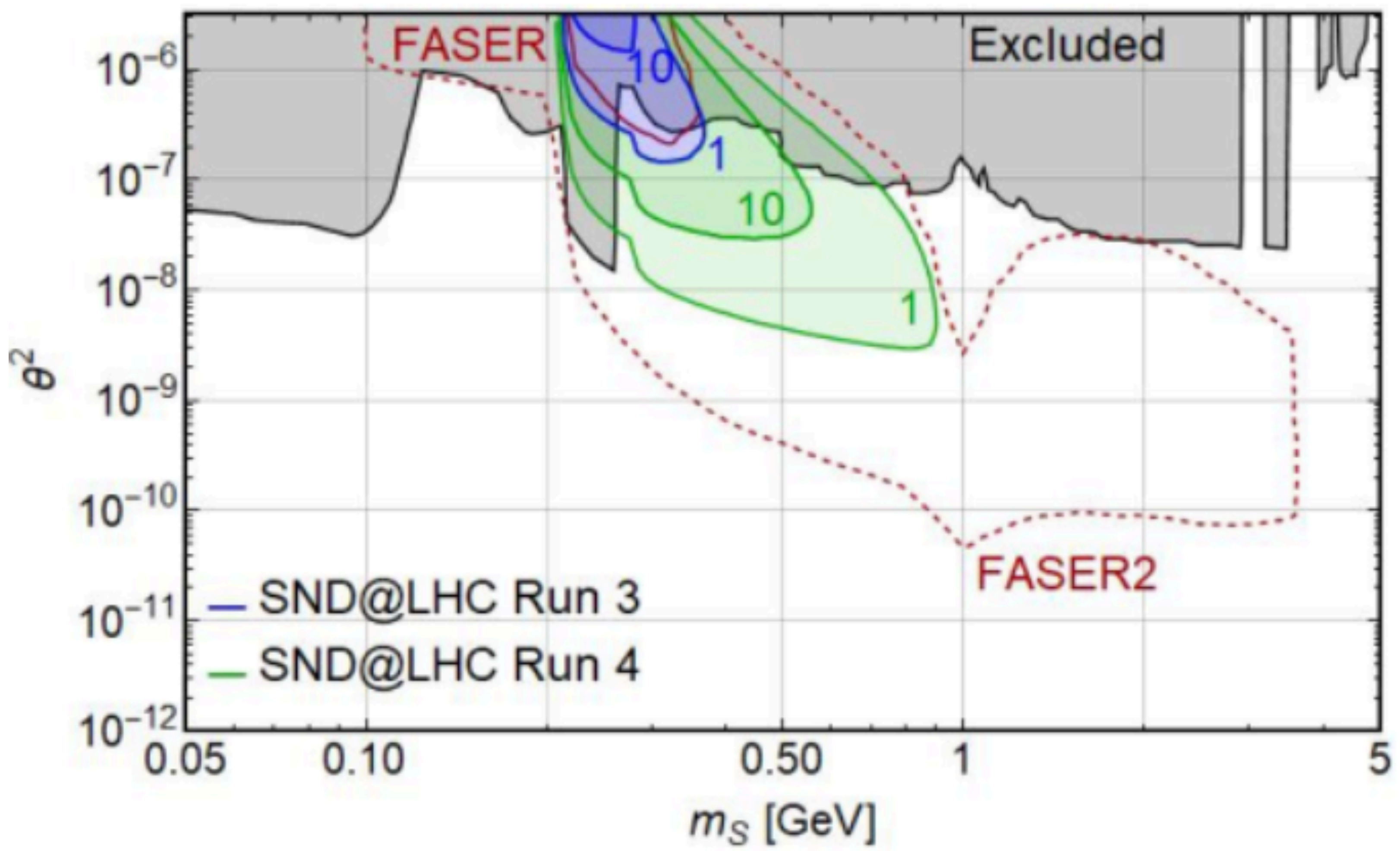
SND@LHC

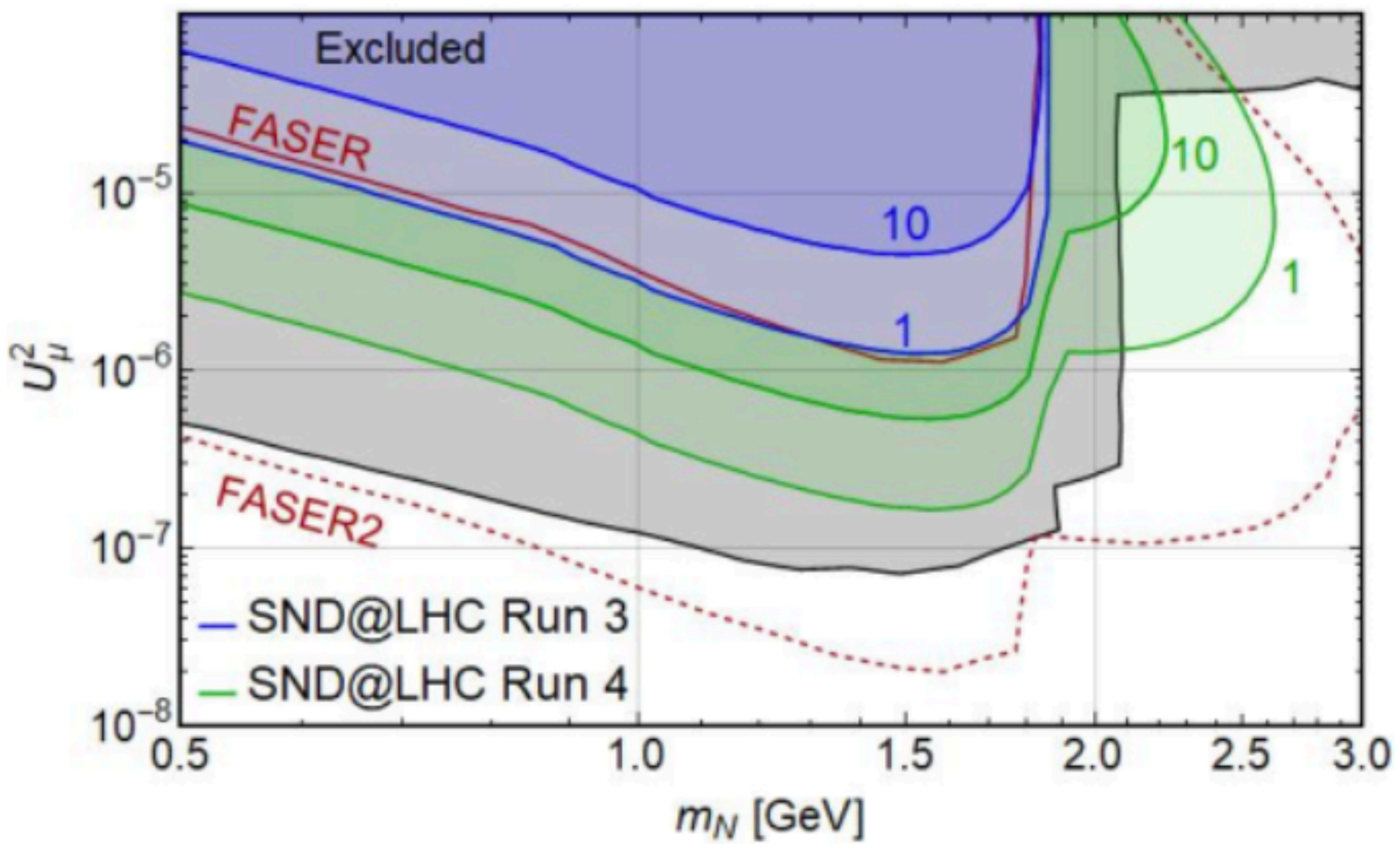
Scattering and Neutrino Detector at the LHC

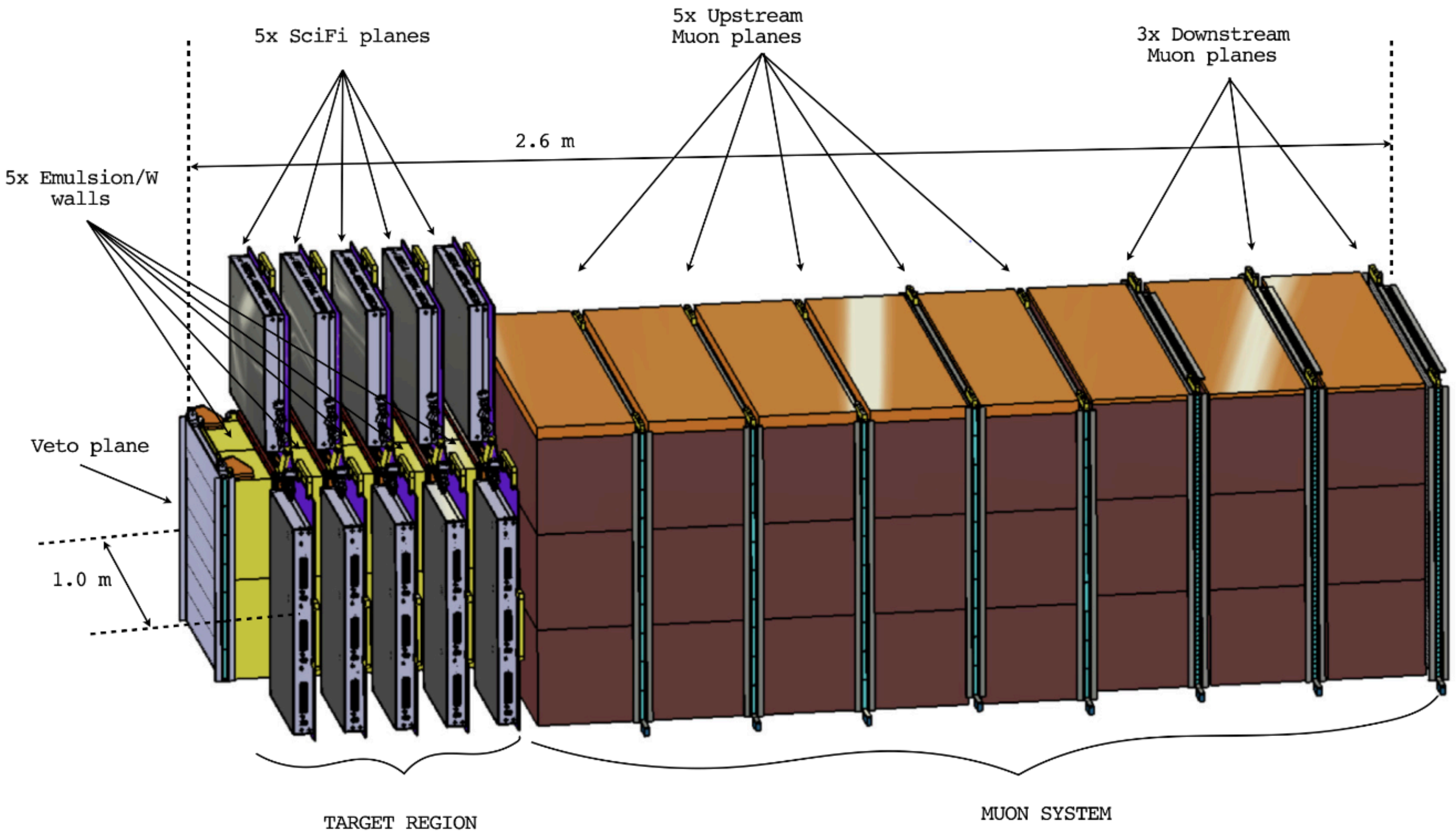
JHEP03(2022)006

Dark Scalar

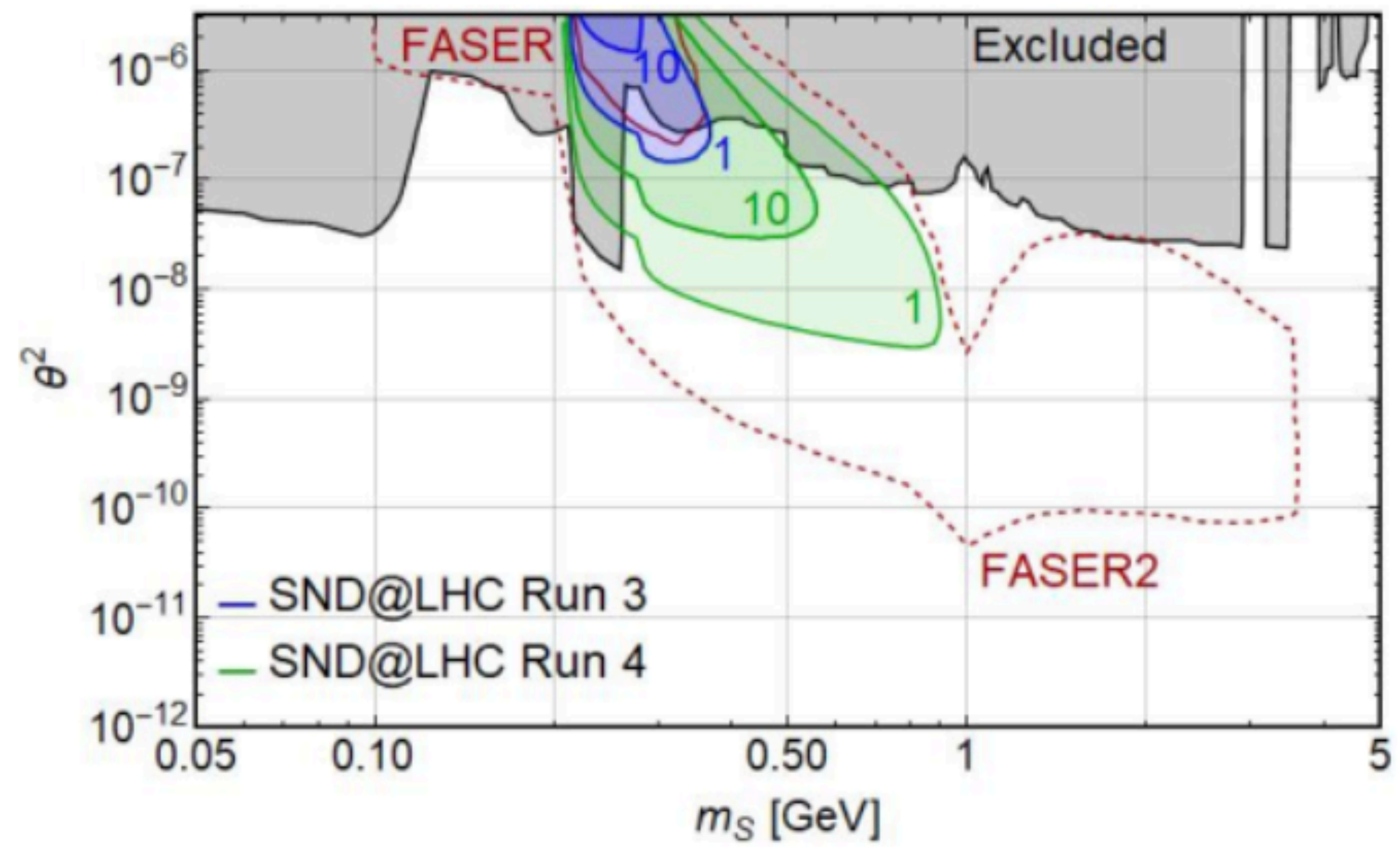


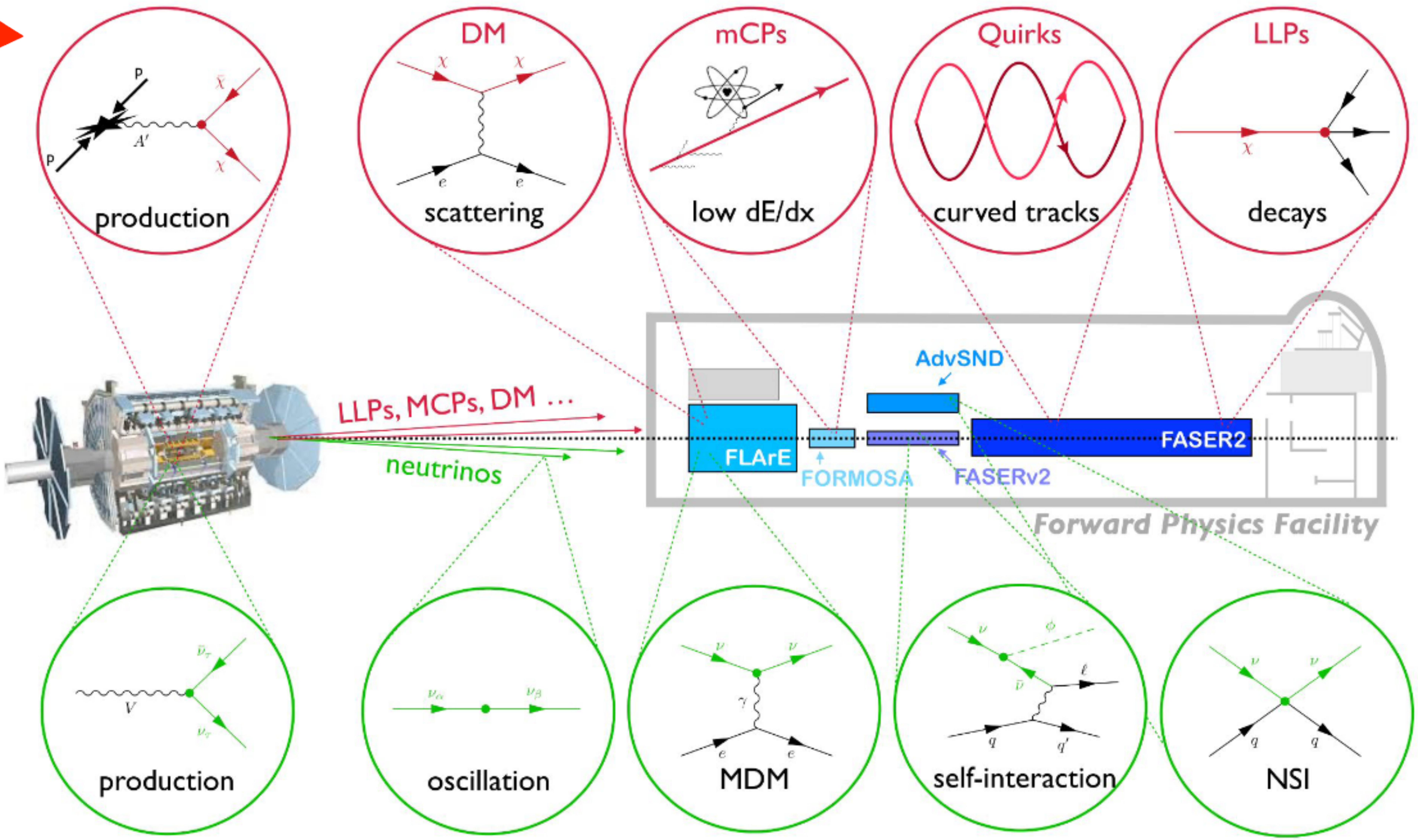
HNL

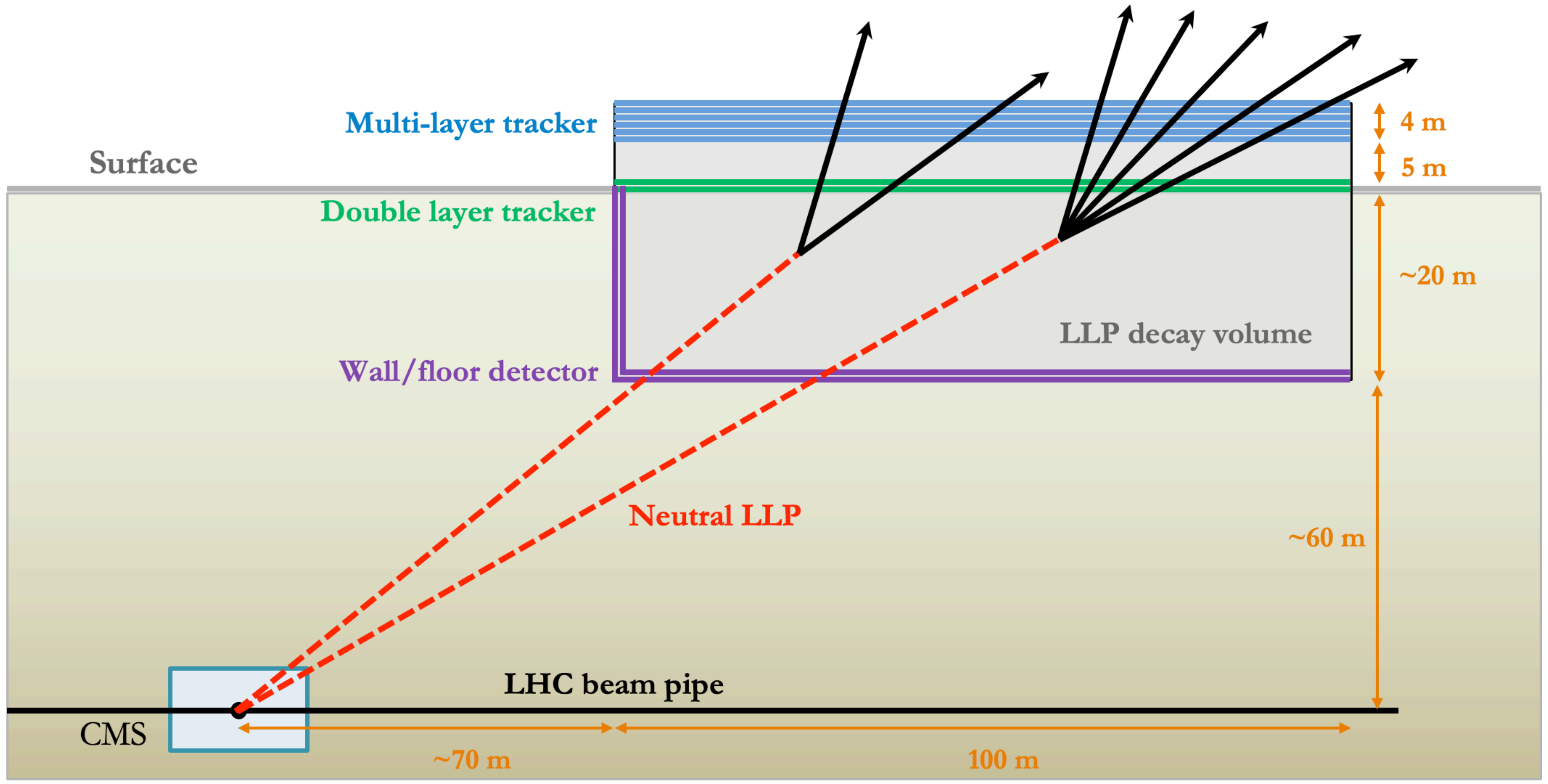




Dark Photon

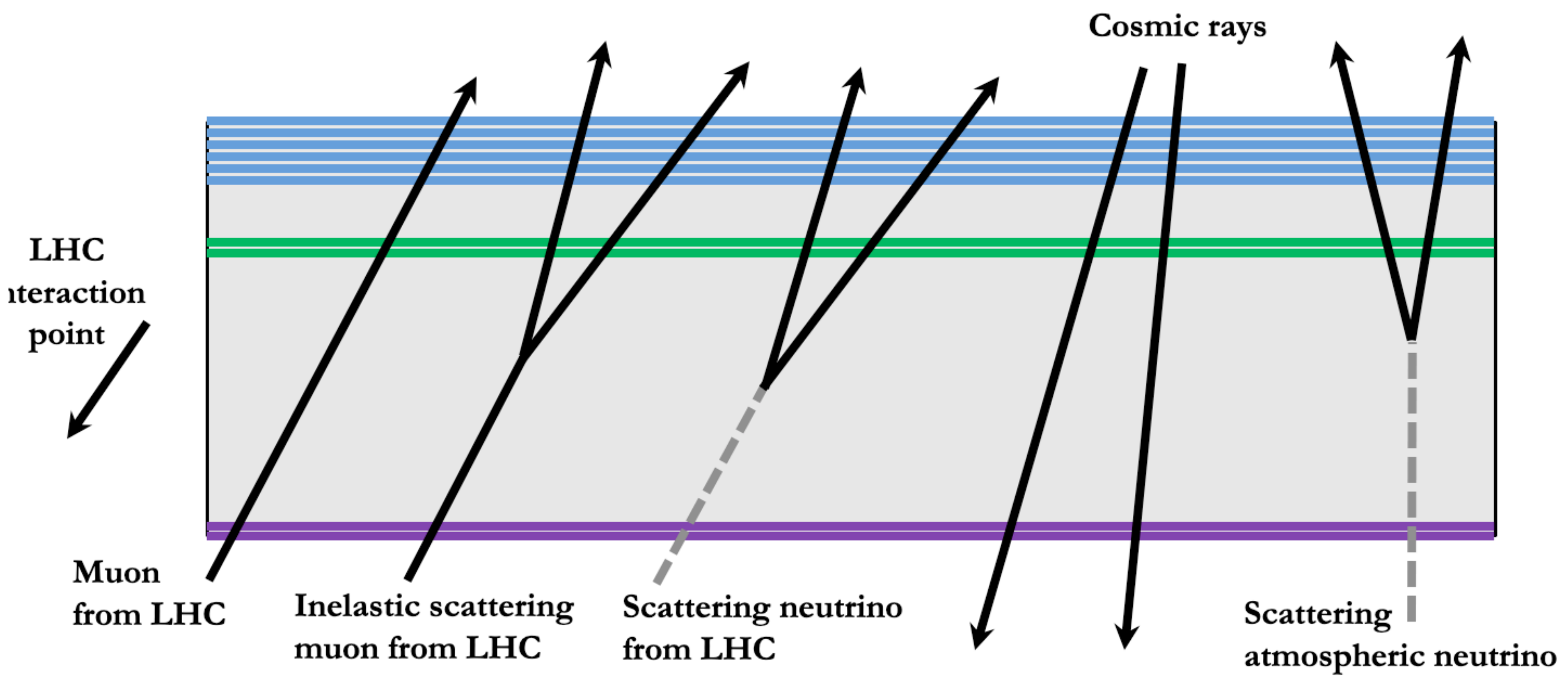


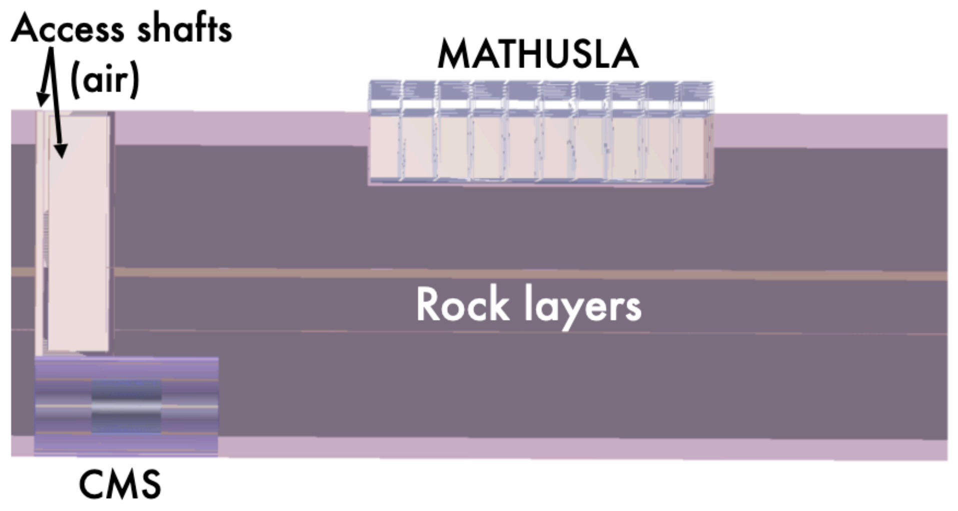

production
DM
scattering
mCPs
low dE/dx
Quirks
curved tracks
LLPs
decays
LLPs, MCPs, DM ...
neutrinos
AdvSND
FLArE
FORMOSA
FASERv2
FASER2
Forward Physics Facility
production
oscillation
MDM
self-interaction
NSI



9 x 9 units, each with a 9 m x 9 m footprint, 30 m tall

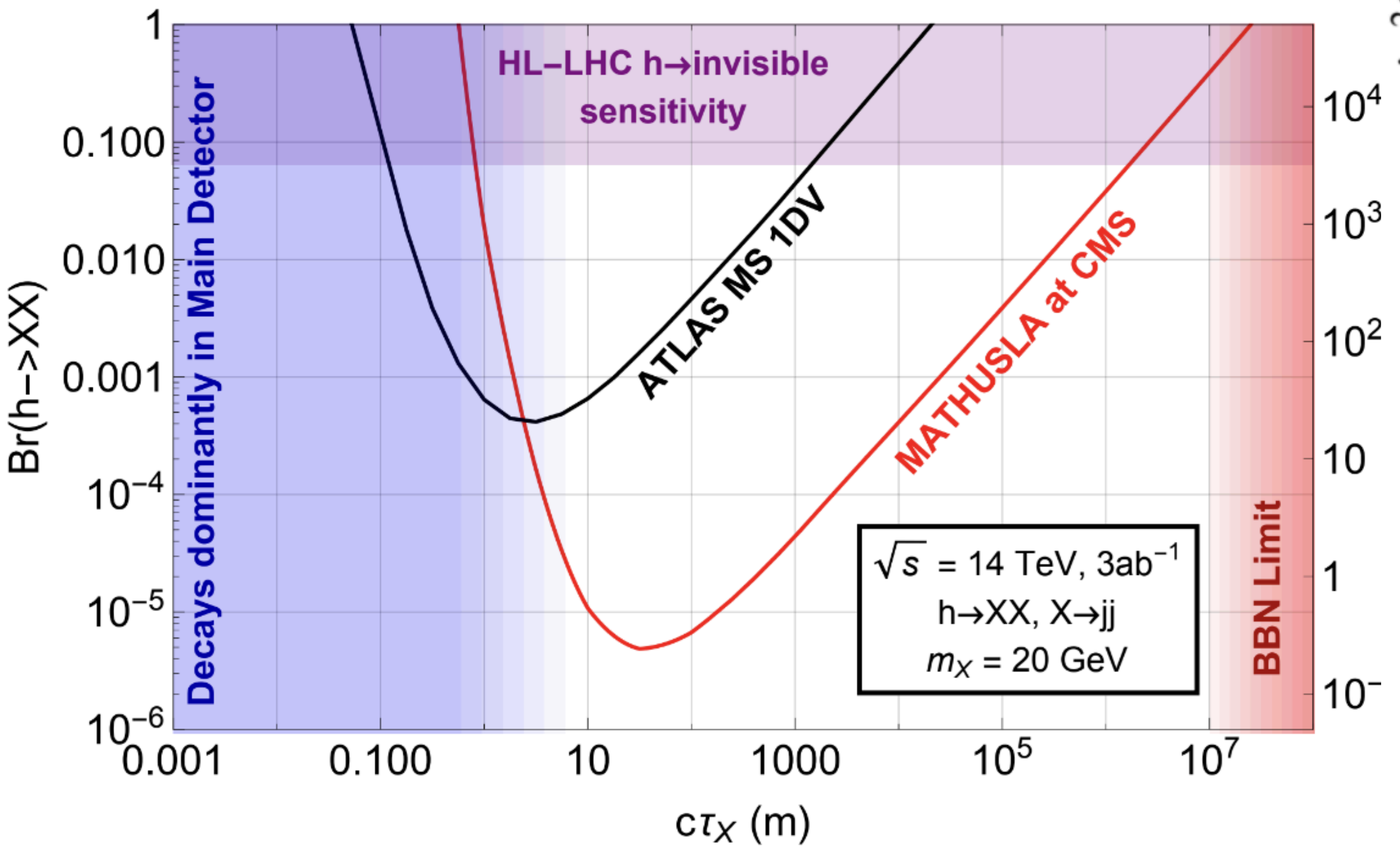
MATHUSLA (Massive Timing Hodoscope for Ultra Stable neutraL pArticles)

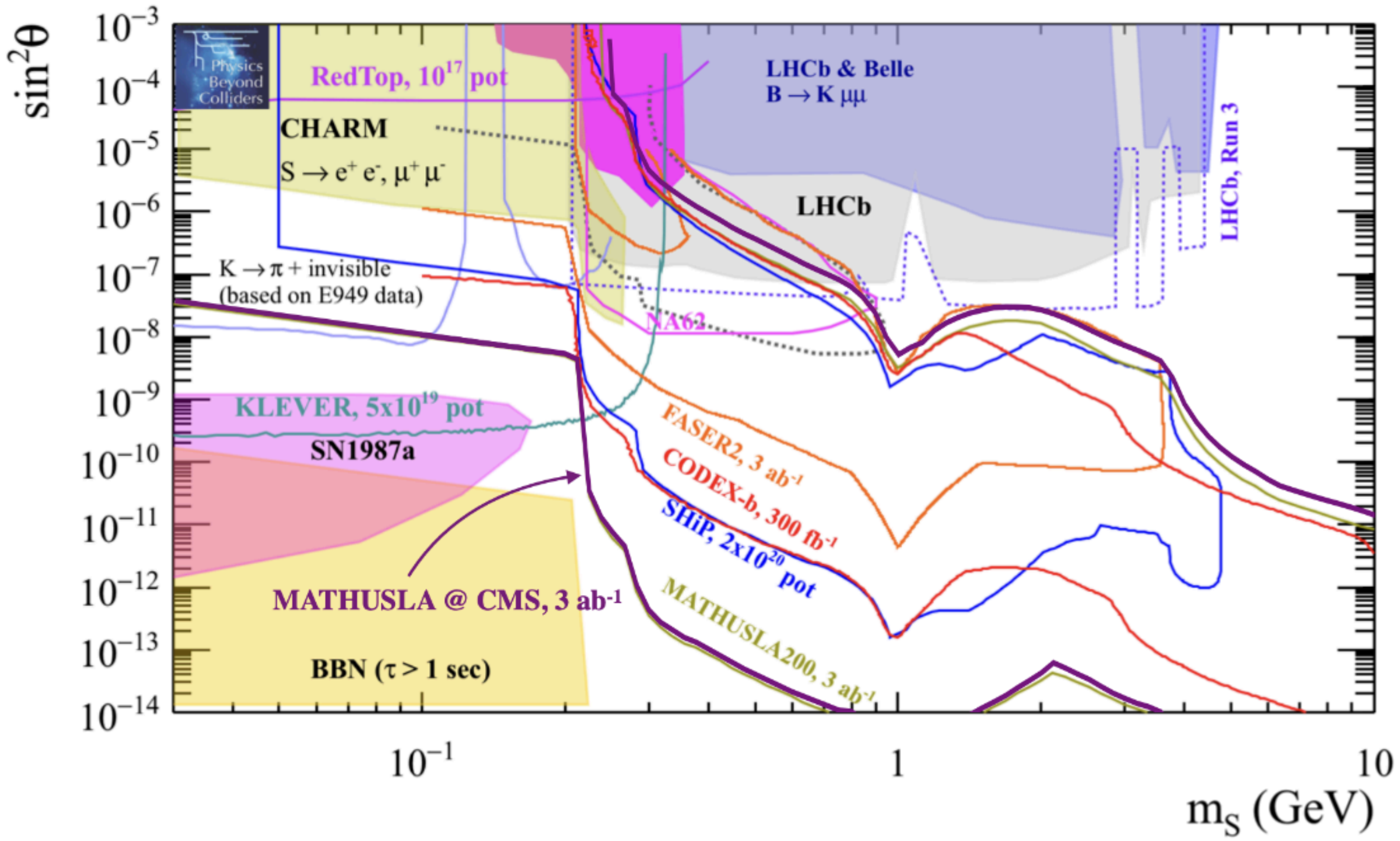


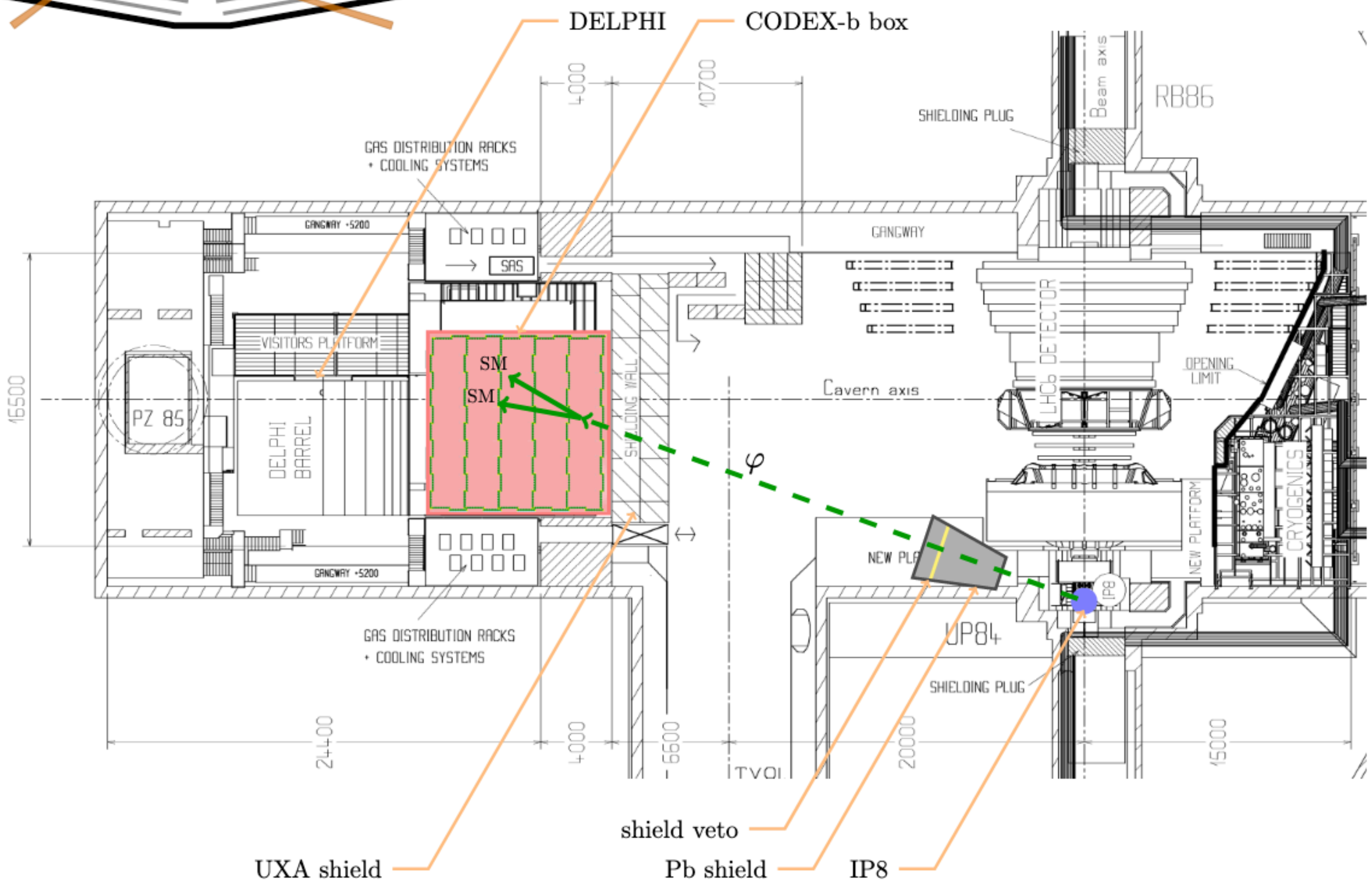


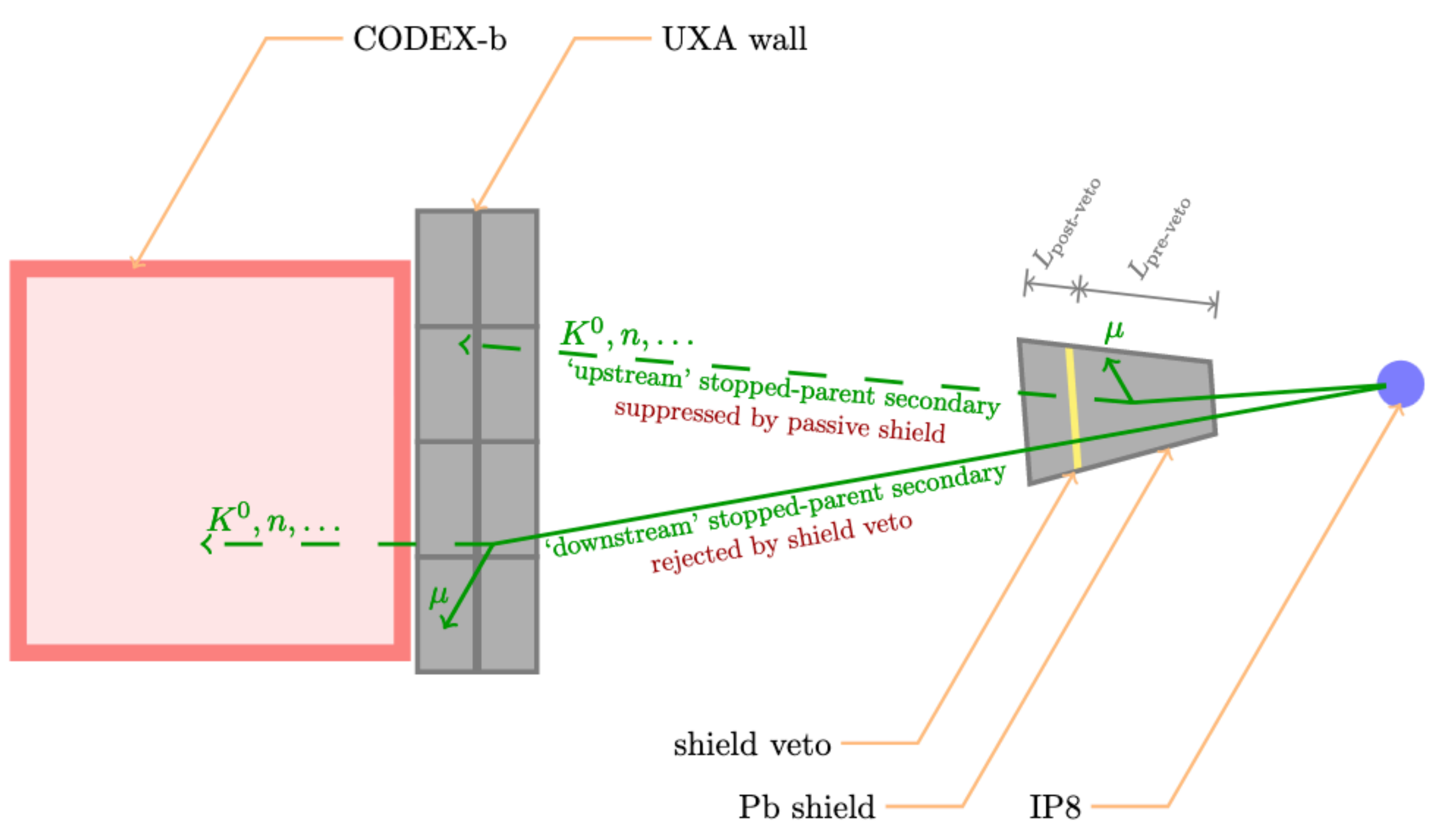
~1000x increased sensitivity compared ATLAS for Higgs neutral, hadronically-decaying LLPs

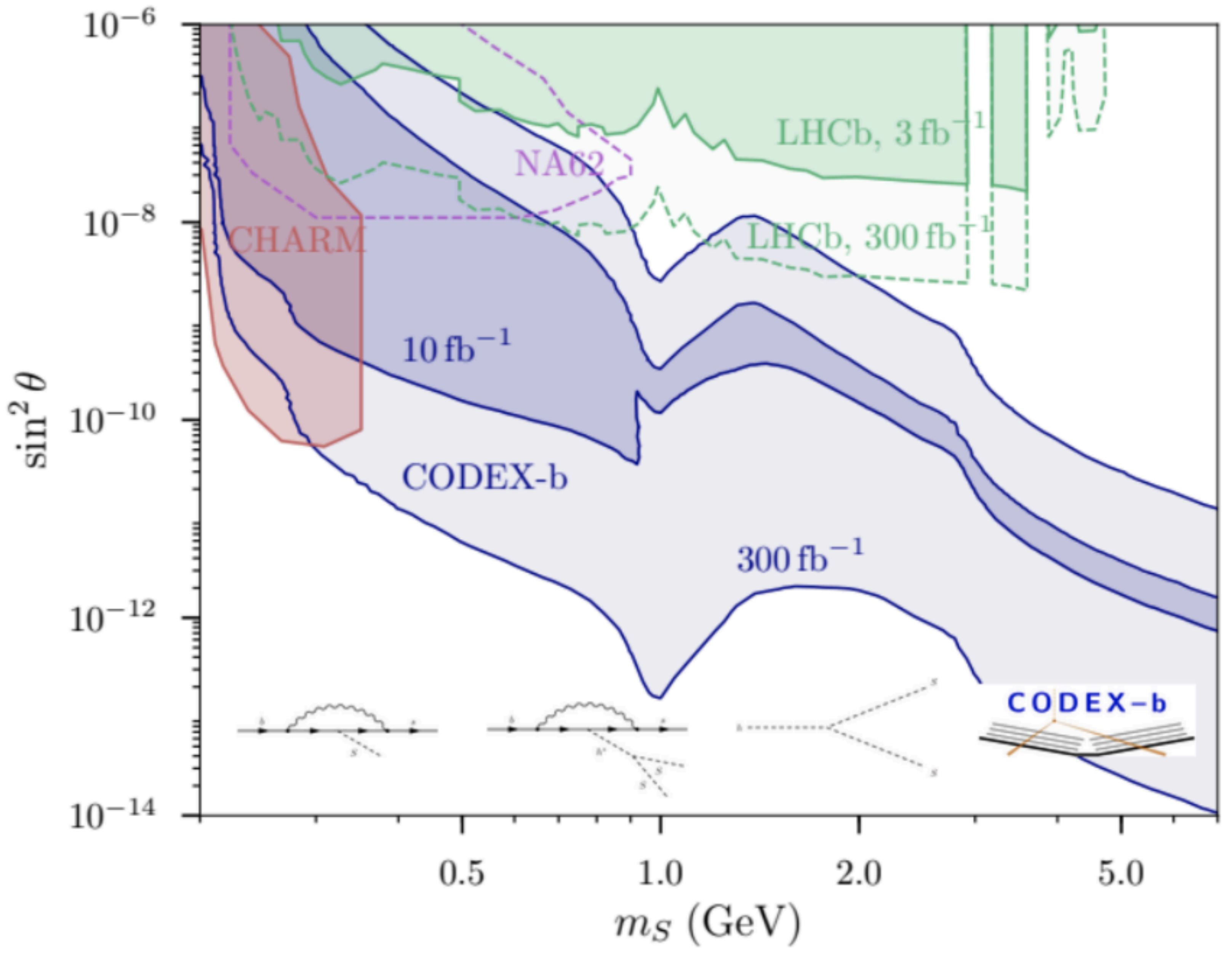
Sensitivity to small mixing angles for Singlet scalar s mixing with SM Higgs, BR(H → ss)



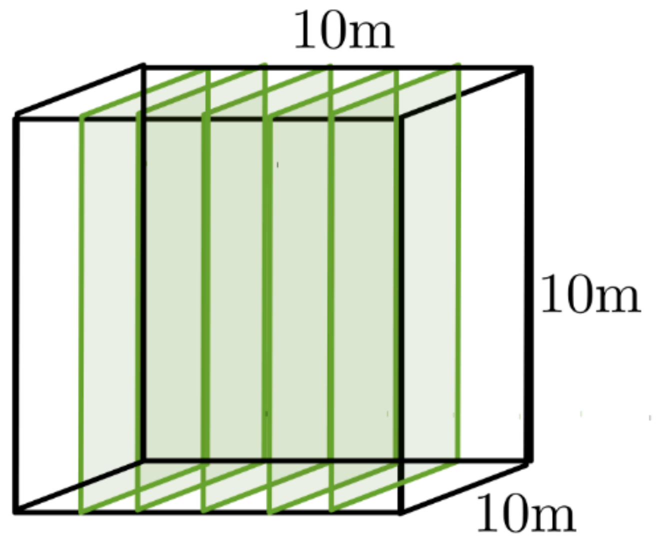








$H^0 \to SS$, where S =Dark Scalar



Complementary coverage of LLP parameter space.
Sensitivity to NP with heavy intermediates e.g. Higgs

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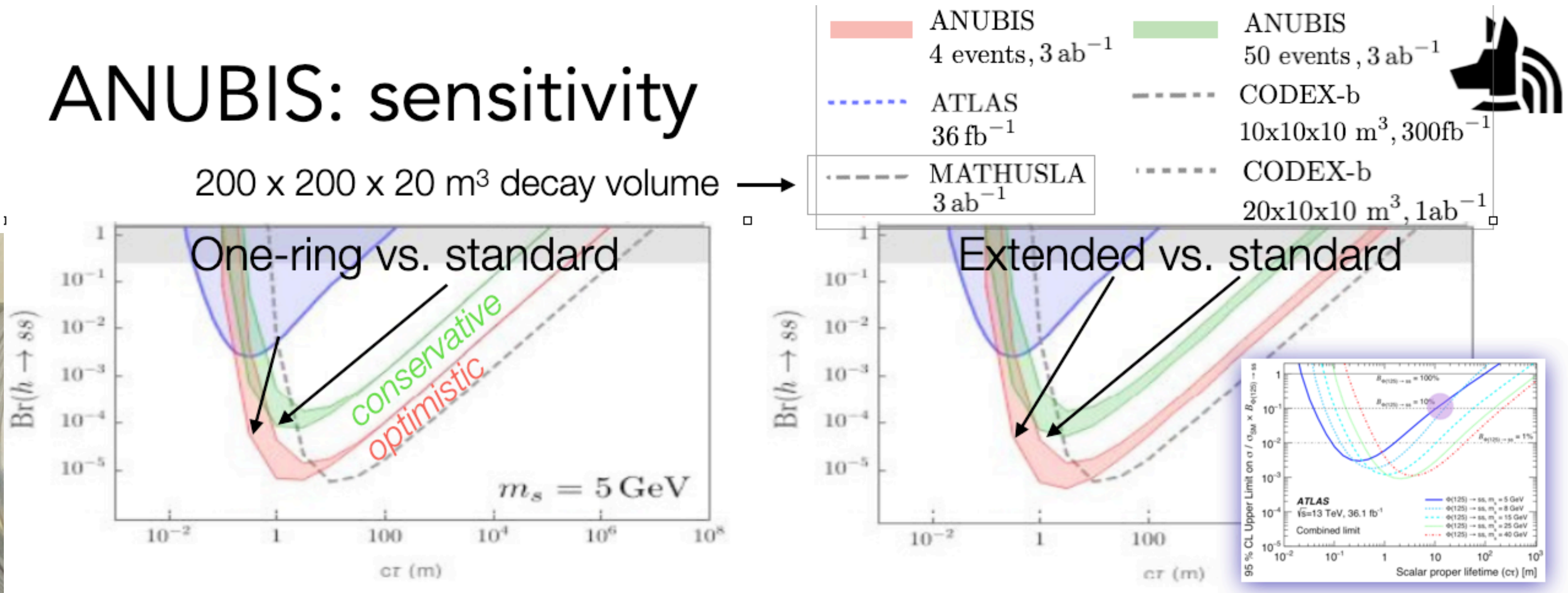
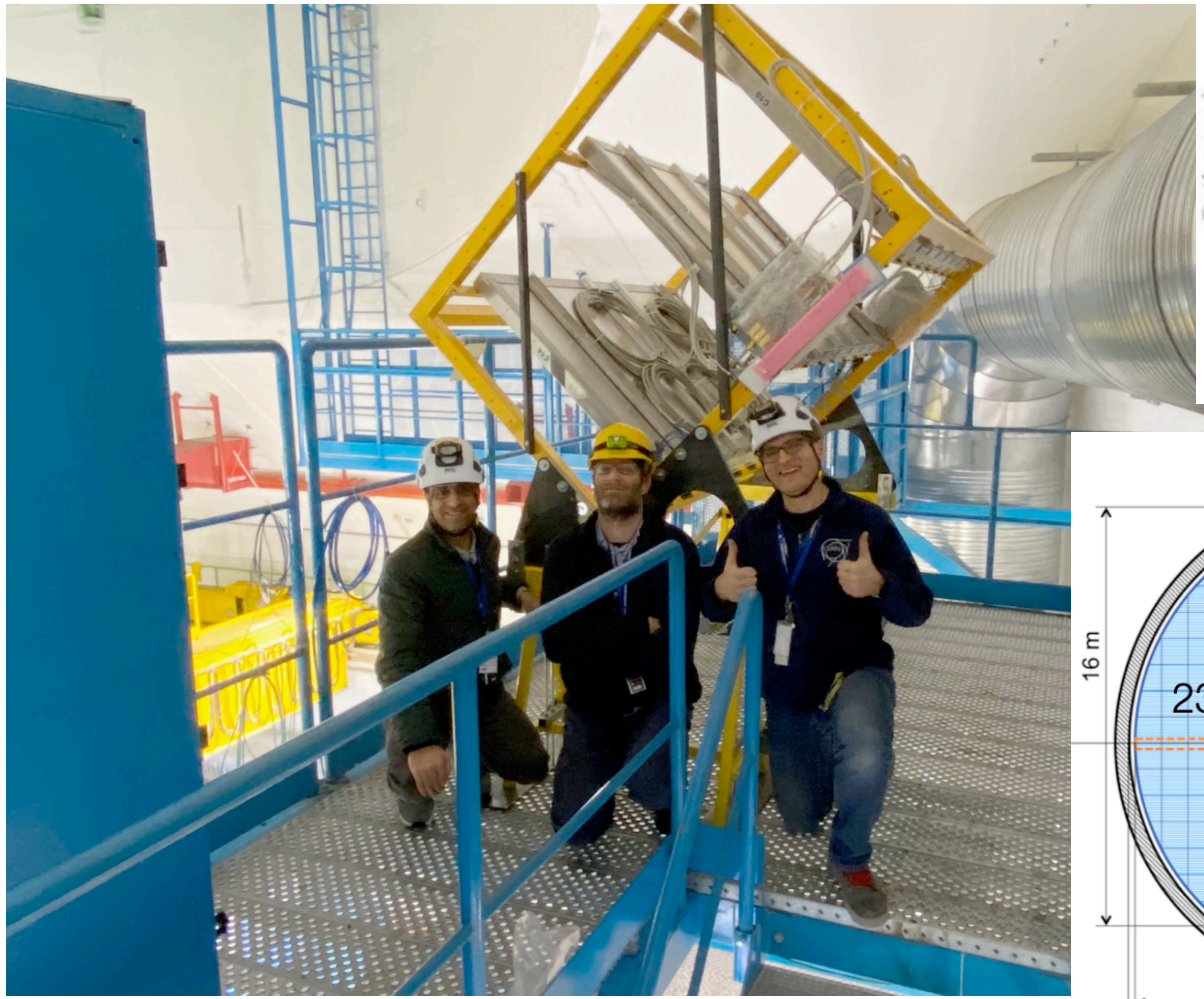
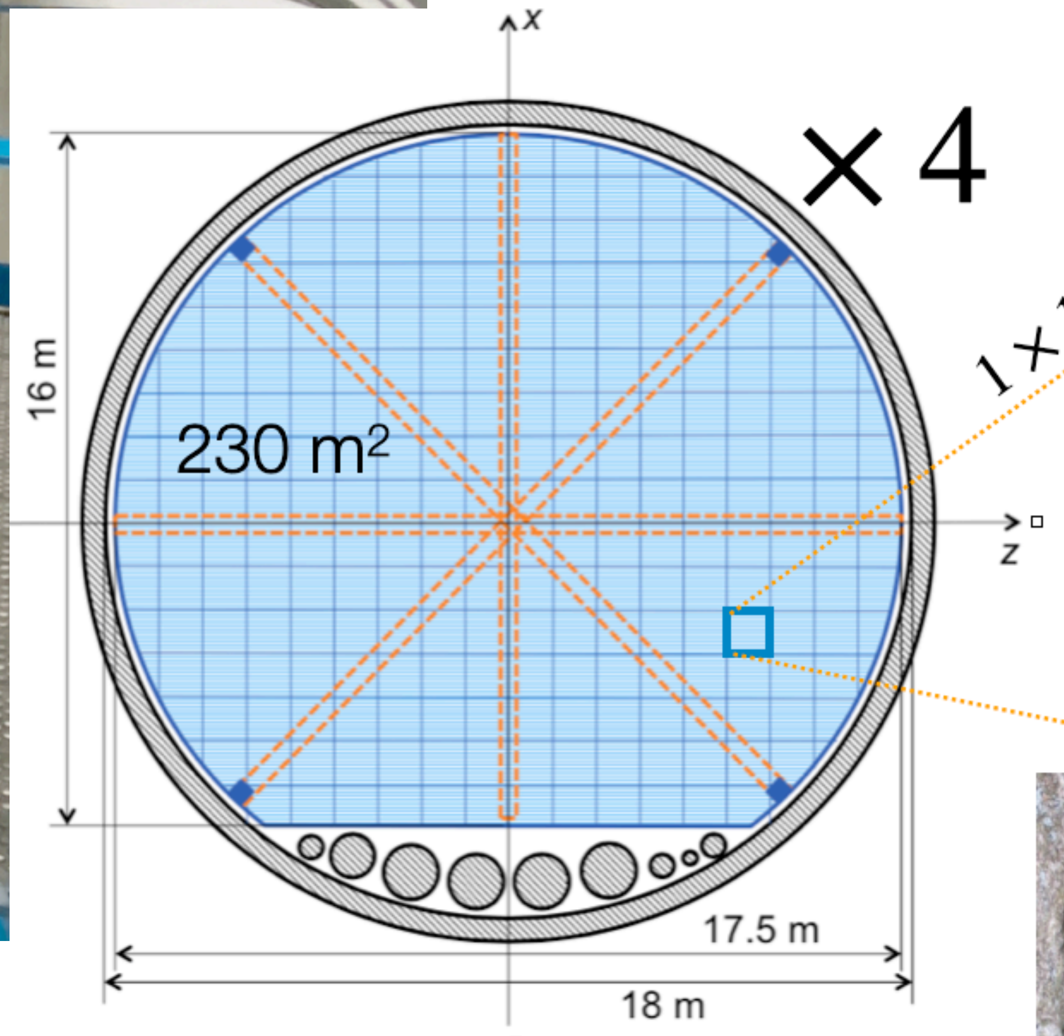
ANUBIS

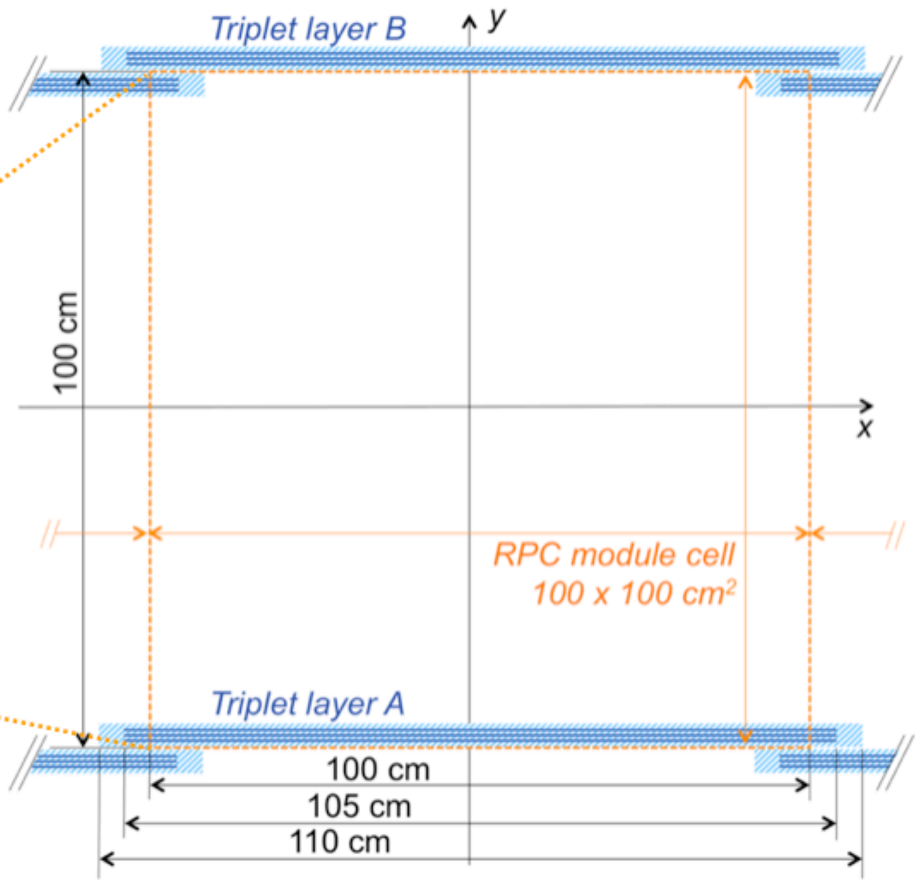
ANUBIS: sensitivity

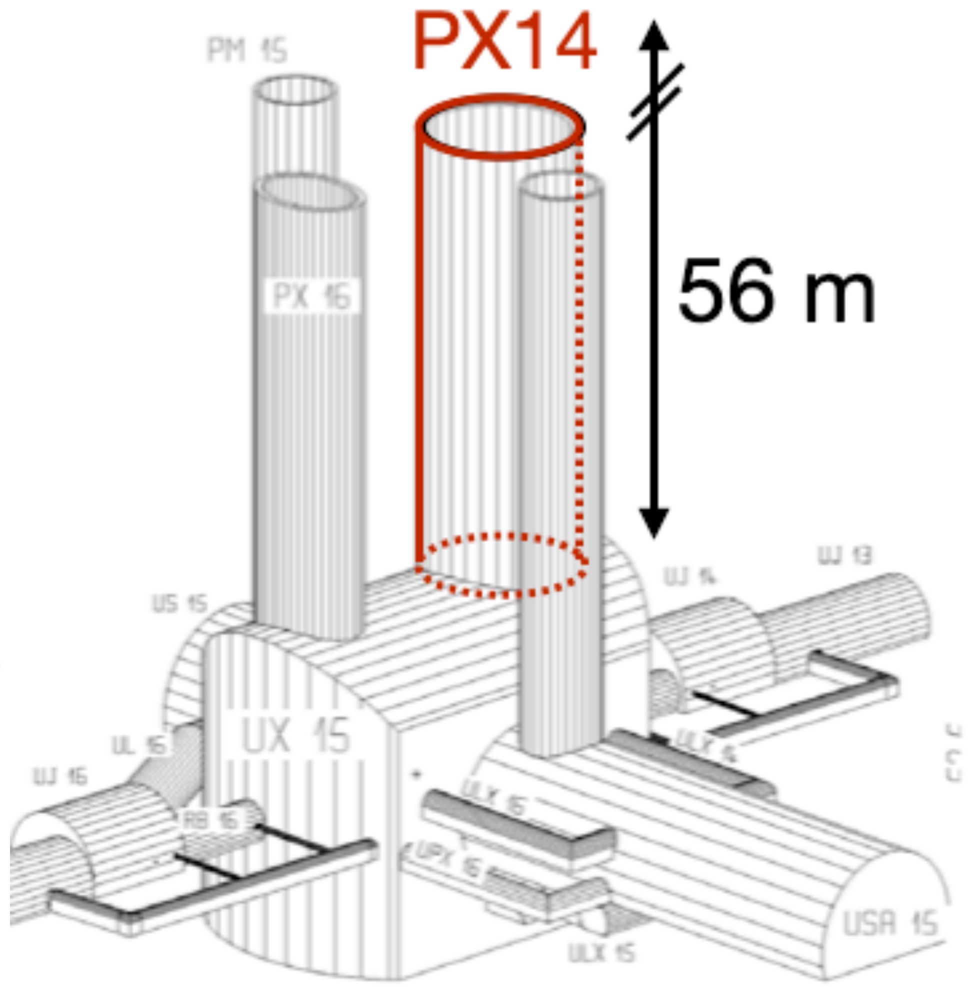
200 x 200 x 20 m³ decay volume →









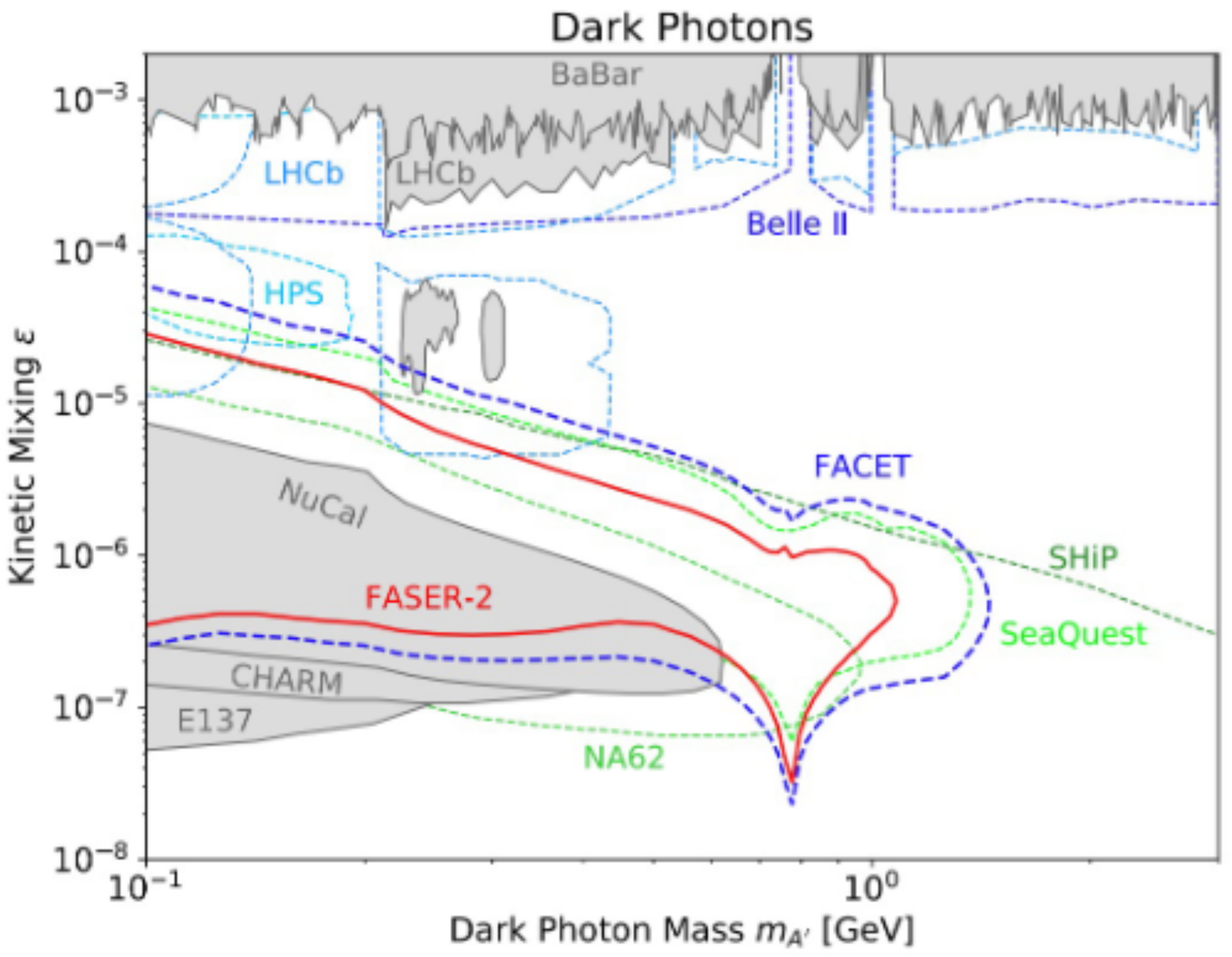


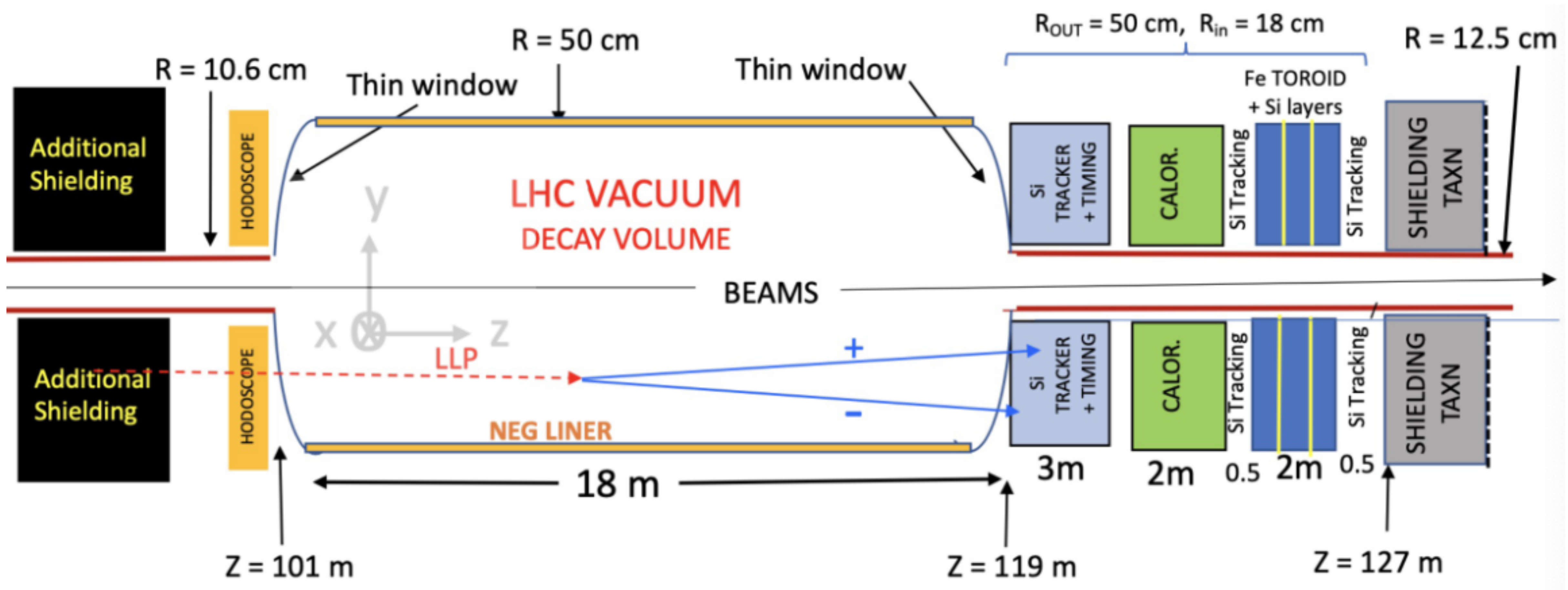
ANUBIS improves the LHC sensitivity by 2-3 orders of magnitude at large decay lengths > 10 m for electrically neutral LLPs with masses > 1 GeV for relatively low cost

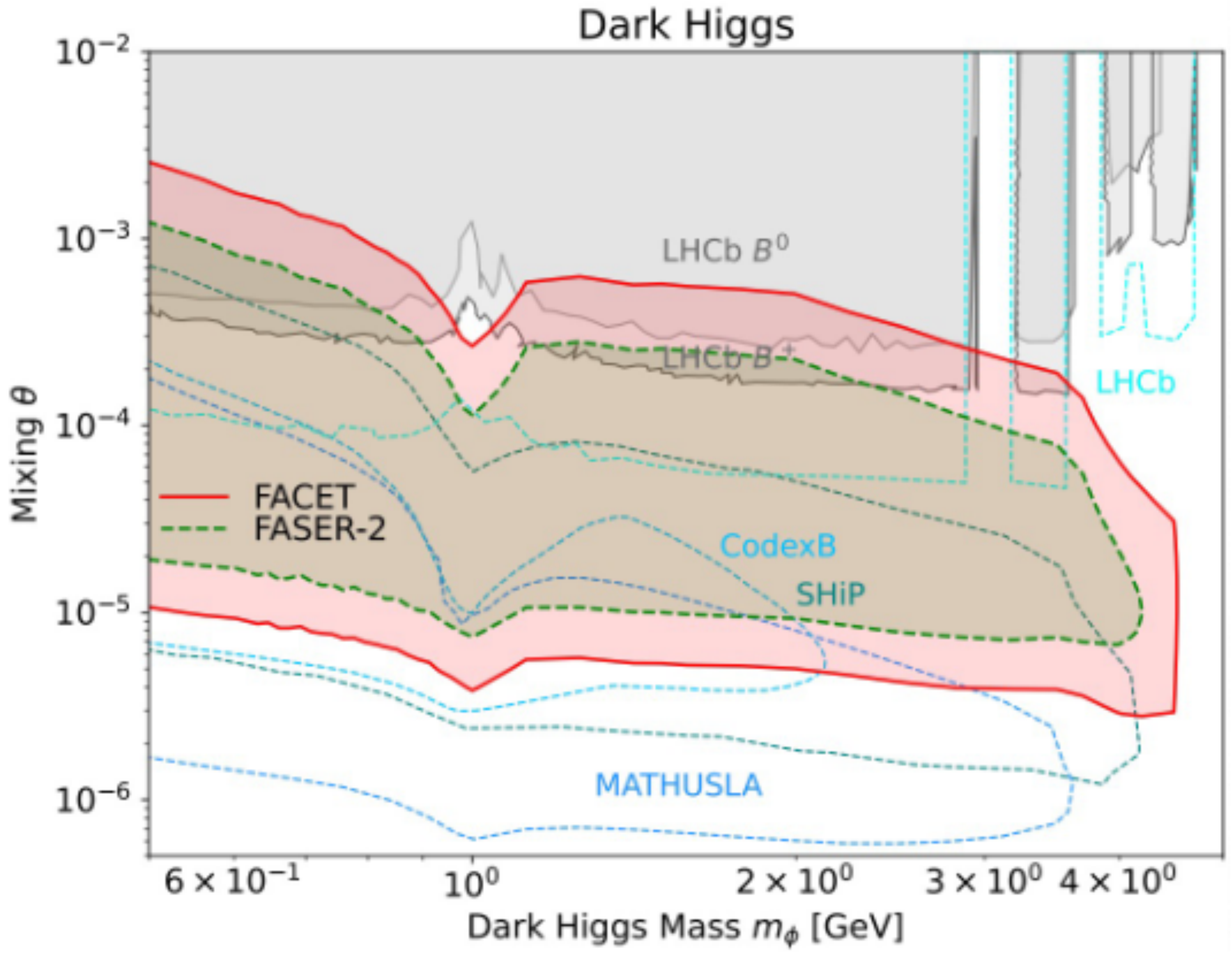
Tracking stations affixed with cams: extract tracking stations to surface quickly & easily in an emergency

Parameter	Specification
Time resolution	$\delta t \lesssim 0.5$ ns
Angular resolution	$\delta\alpha \lesssim 0.01$ rad
Spatial resolution	$\delta x, \delta z \lesssim 0.5$ cm
Per-layer hit efficiency	$\varepsilon \gtrsim 98\%$

FACET


Dark Photons
BaBar
LHCb
LHCb
Belle II
HPS
FACET
SHiP
SeaQuest
NuCal
FASER-2
CHARM
E137
NA62
Kinetic Mixing ε
Dark Photon Mass $m_{A'}$ [GeV]


R = 10.6 cm
R = 50 cm
Thin window
Thin window
R_{OUT} = 50 cm, R_{in} = 18 cm
R = 12.5 cm
Additional Shielding
HODOSCOPE
LHC VACUUM
DECAY VOLUME
Si TRACKER + TIMING
CALOR.
Si Tracking
Fe TOROID + Si layers
Si Tracking
SHIELDING TAXN
BEAMS
LLP
NEG LINER
18 m
3m
2m
0.5
2m
0.5
Z = 101 m
Z = 119 m
Z = 127 m


Dark Higgs
LHCb B^0
LHCb B^+
LHCb
FACET
FASER-2
CodexB
SHiP
MATHUSLA
Mixing θ
Dark Higgs Mass m_ϕ [GeV]

Kaon and beam dump modes, beam-dump mode sensitive to LLP signatures (HNL, dark photons/scalars, ALPs)

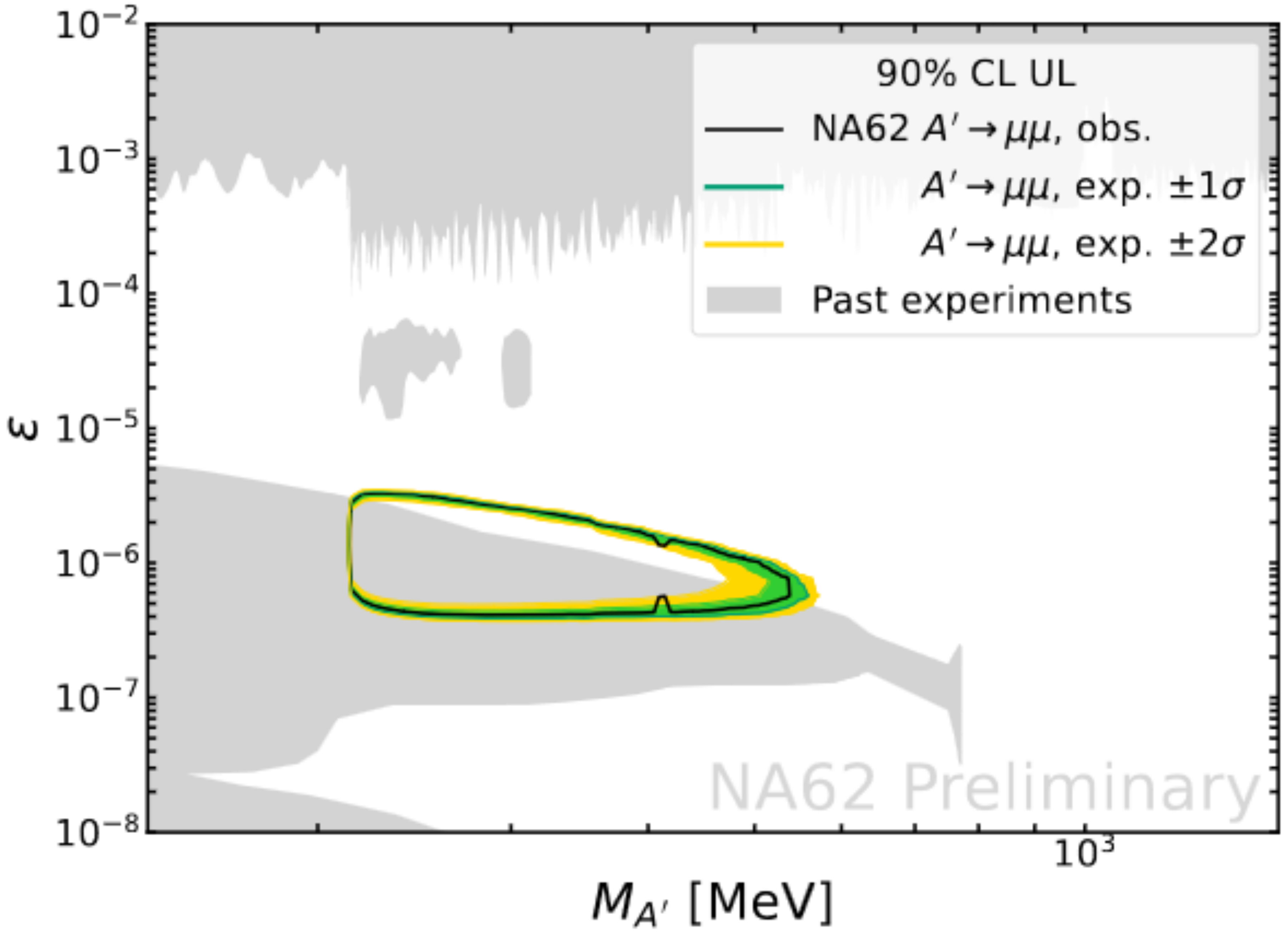
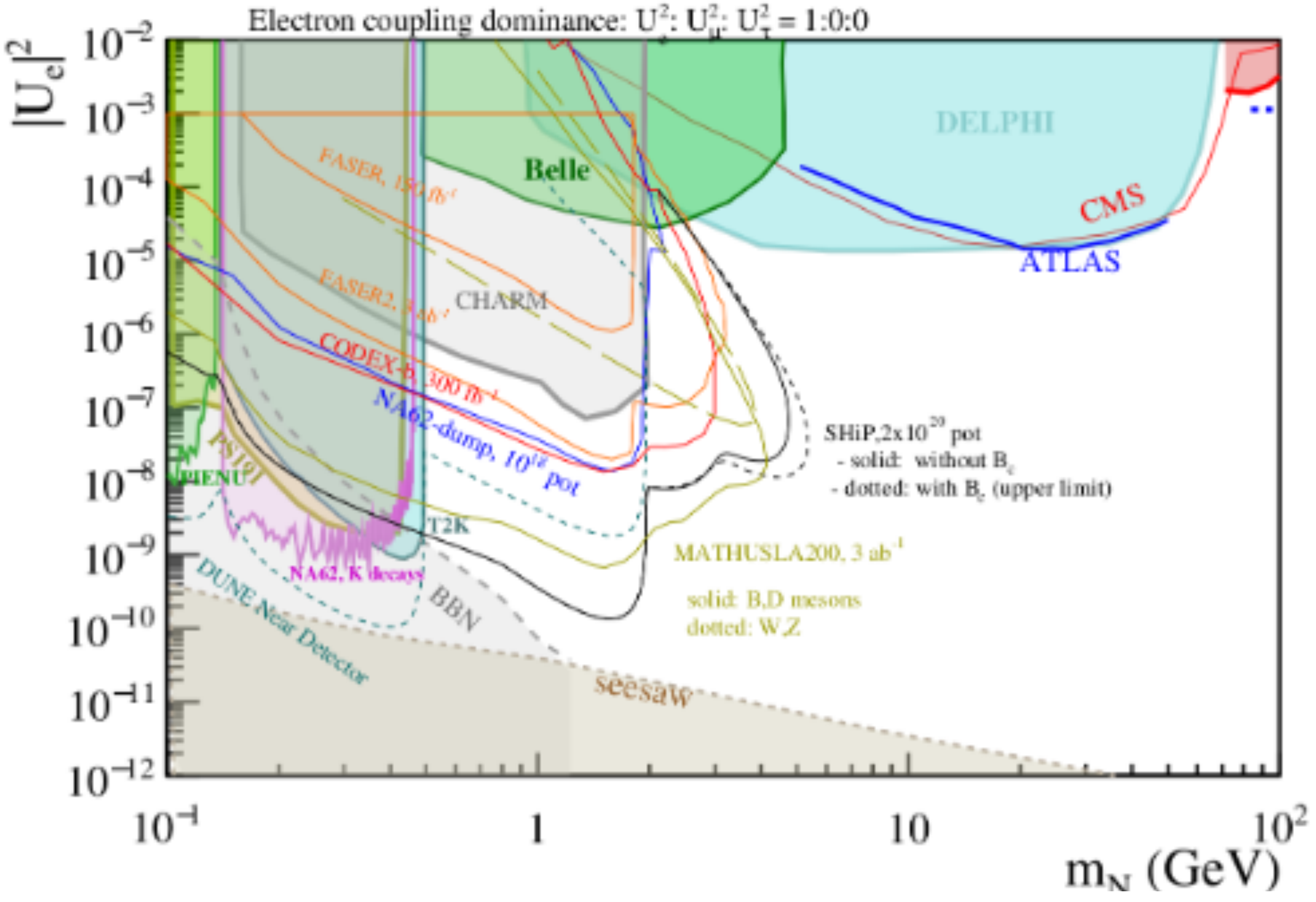
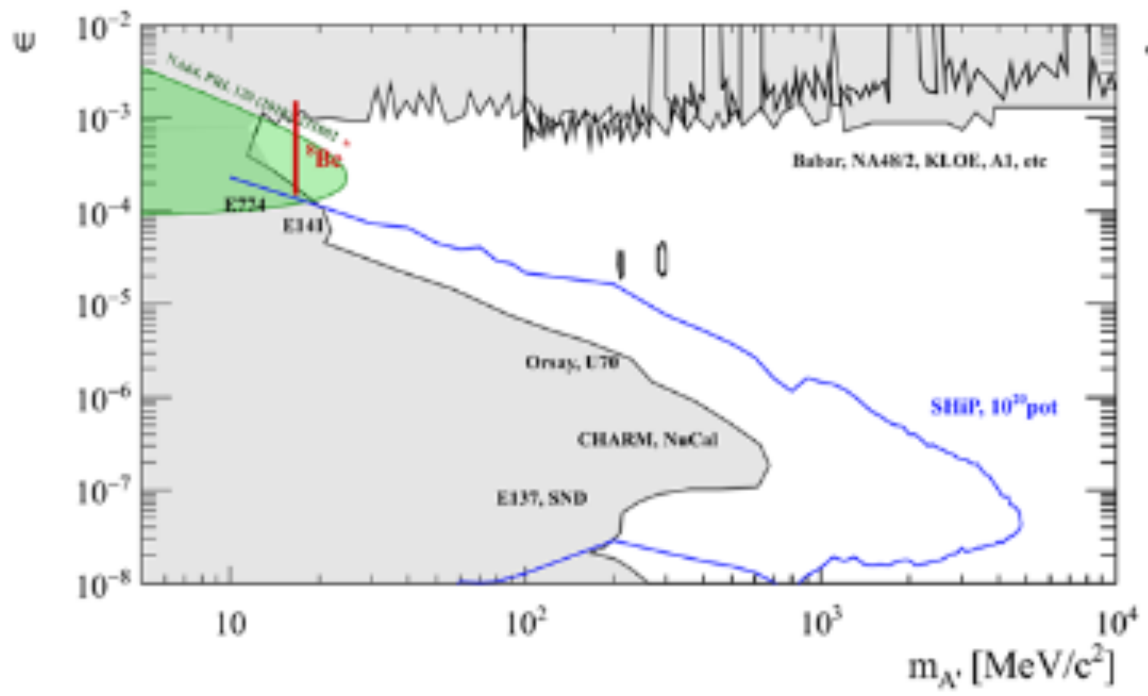


Figure: Final result with upper limit @90% CL.

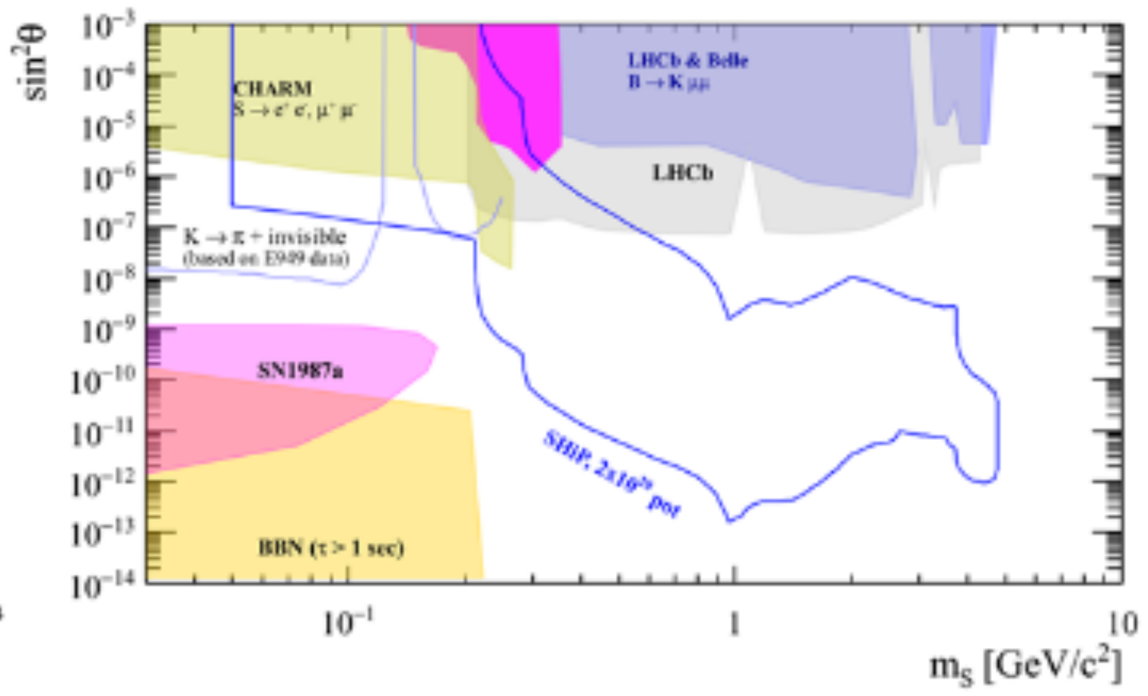


SHiP
Search for Hidden Particles

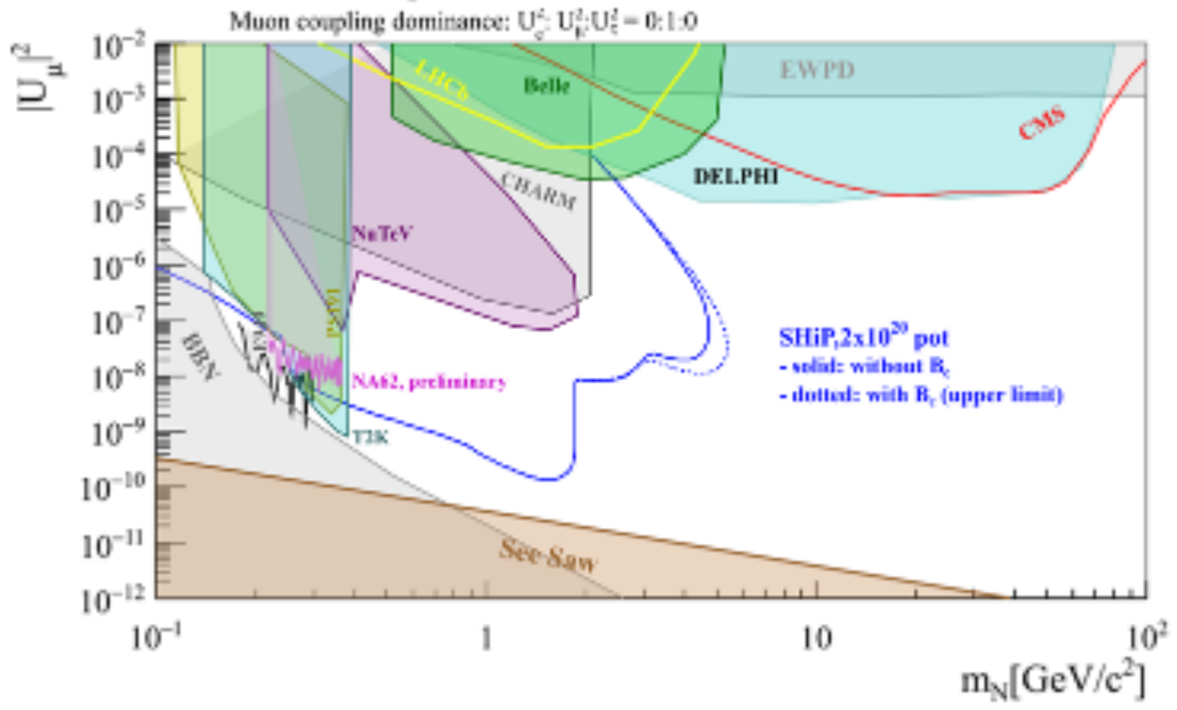
dark photons



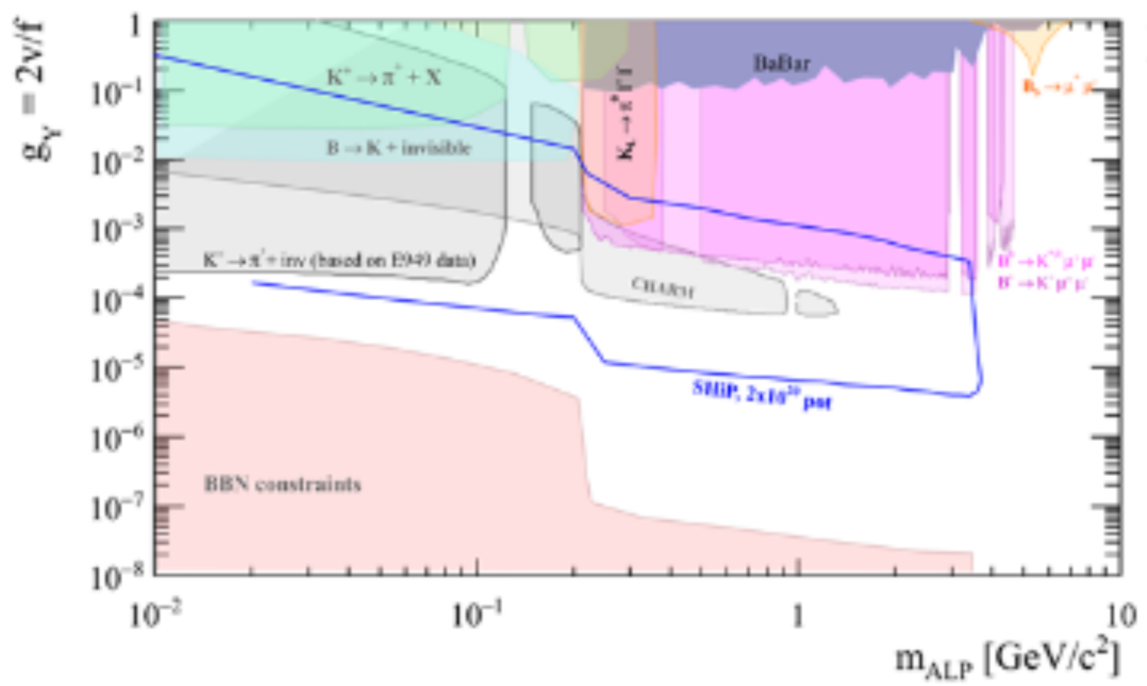
dark scalars



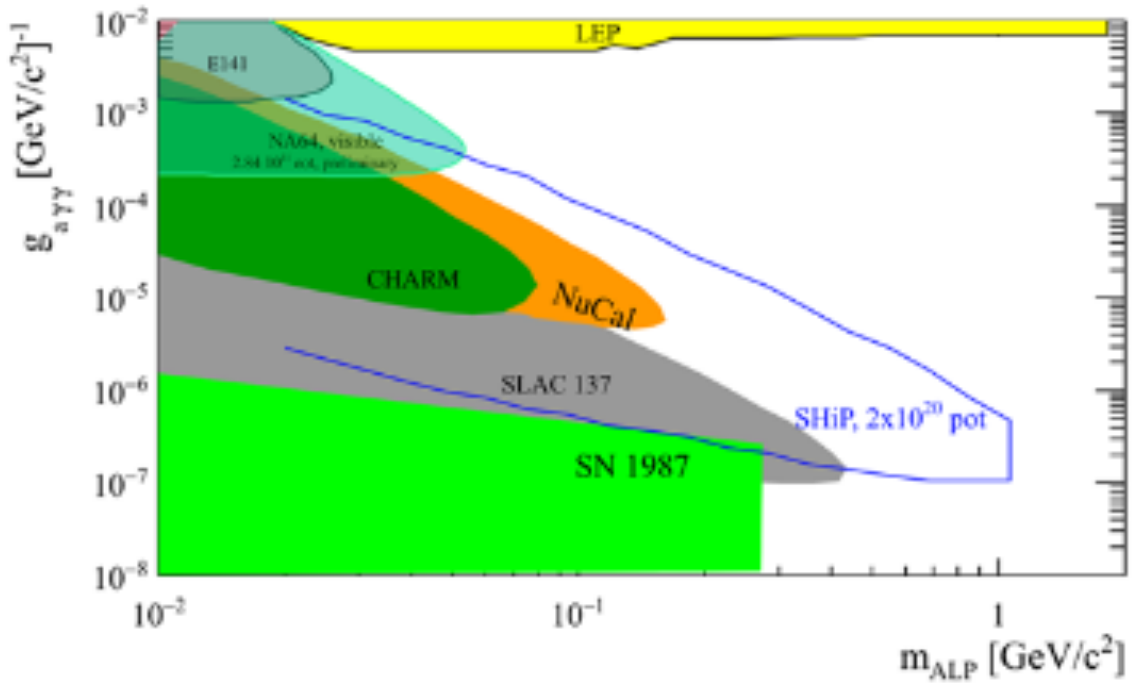
heavy neutral leptons



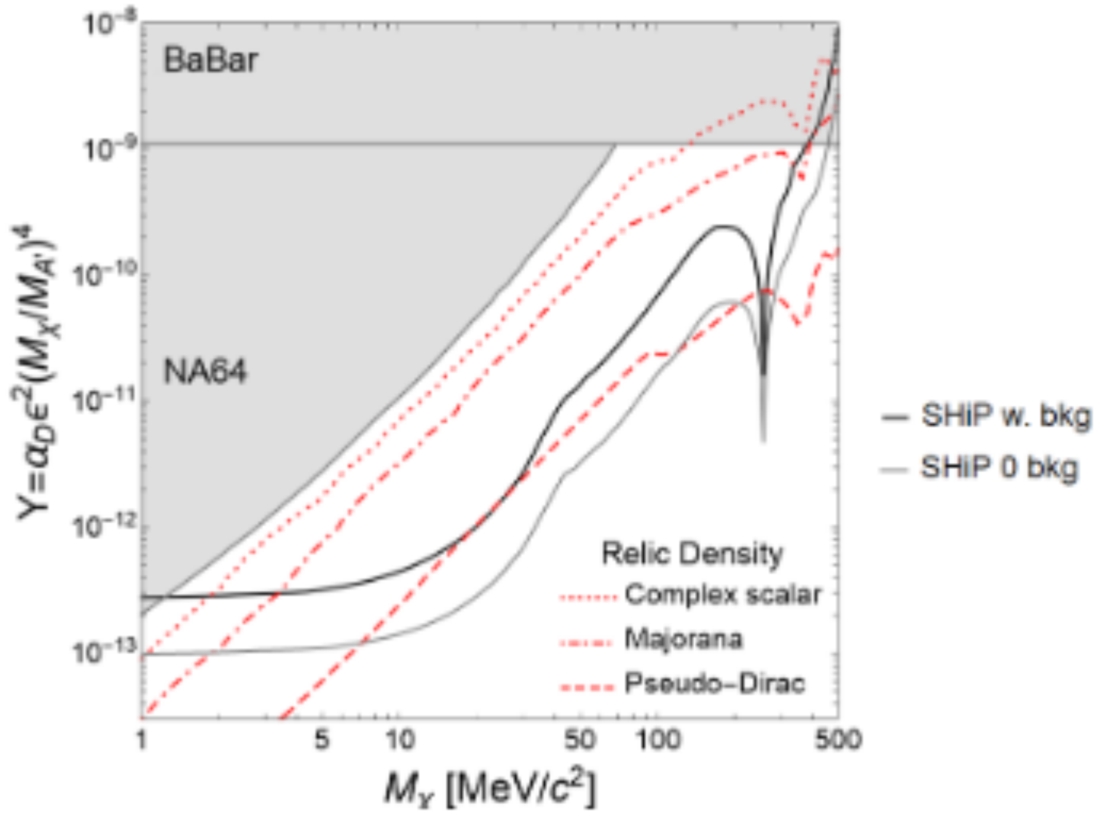
ALPs coupled to fermions

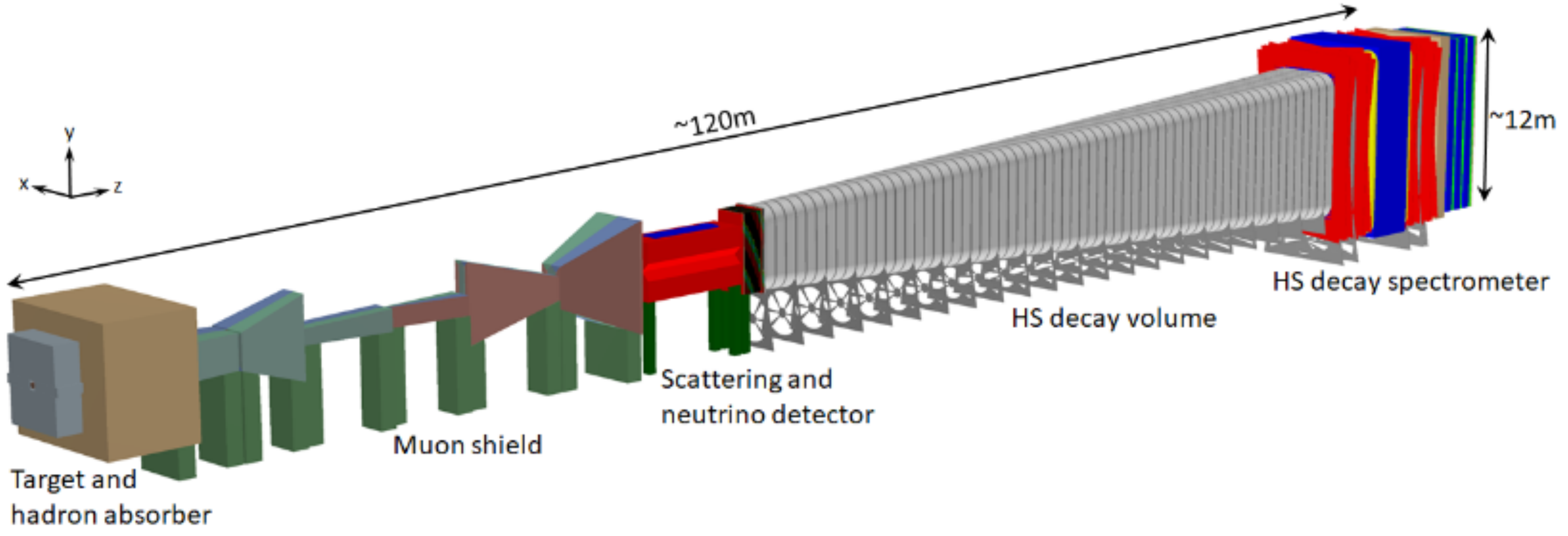


… and to photons



light dark matter jhep04





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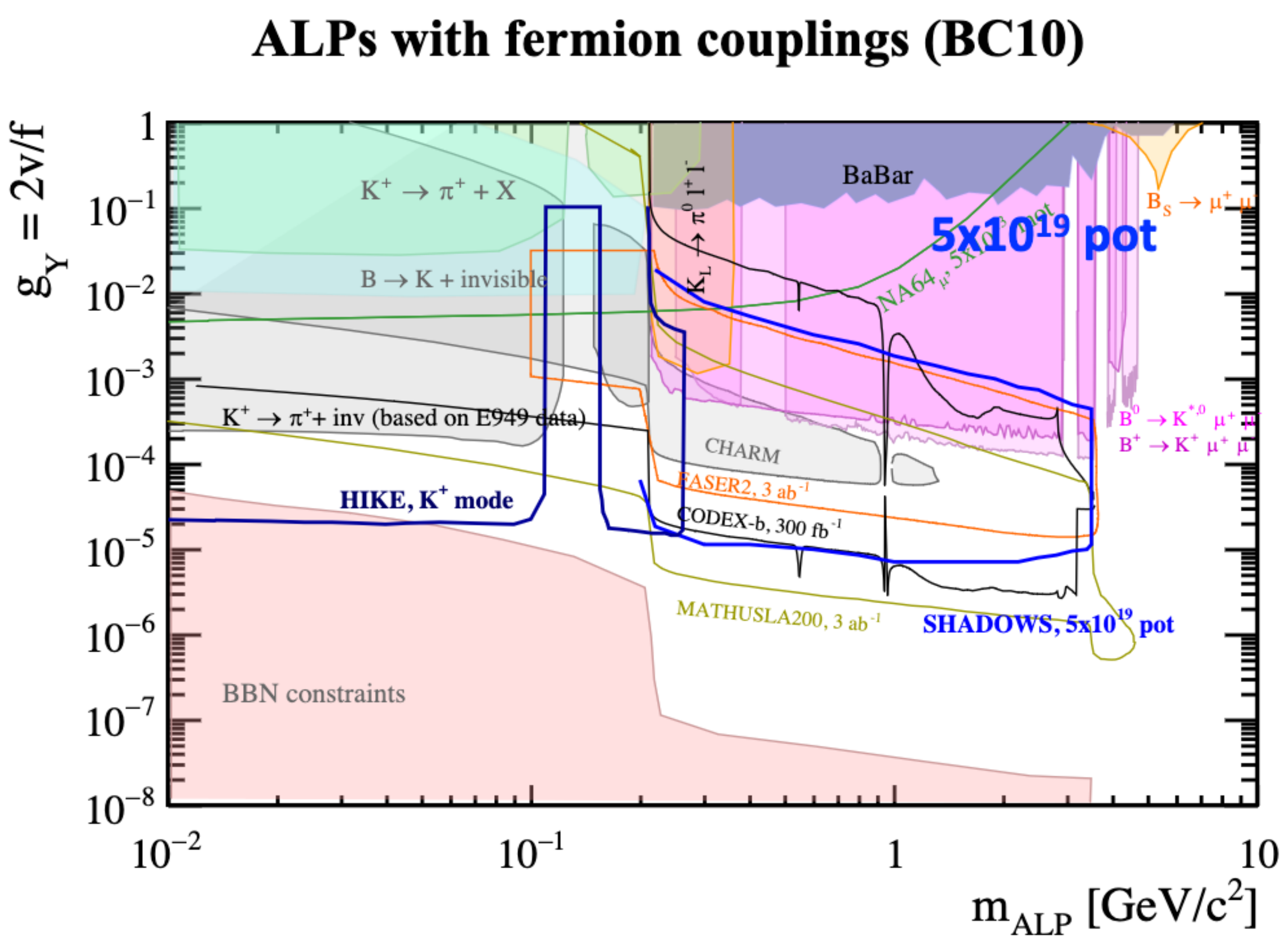
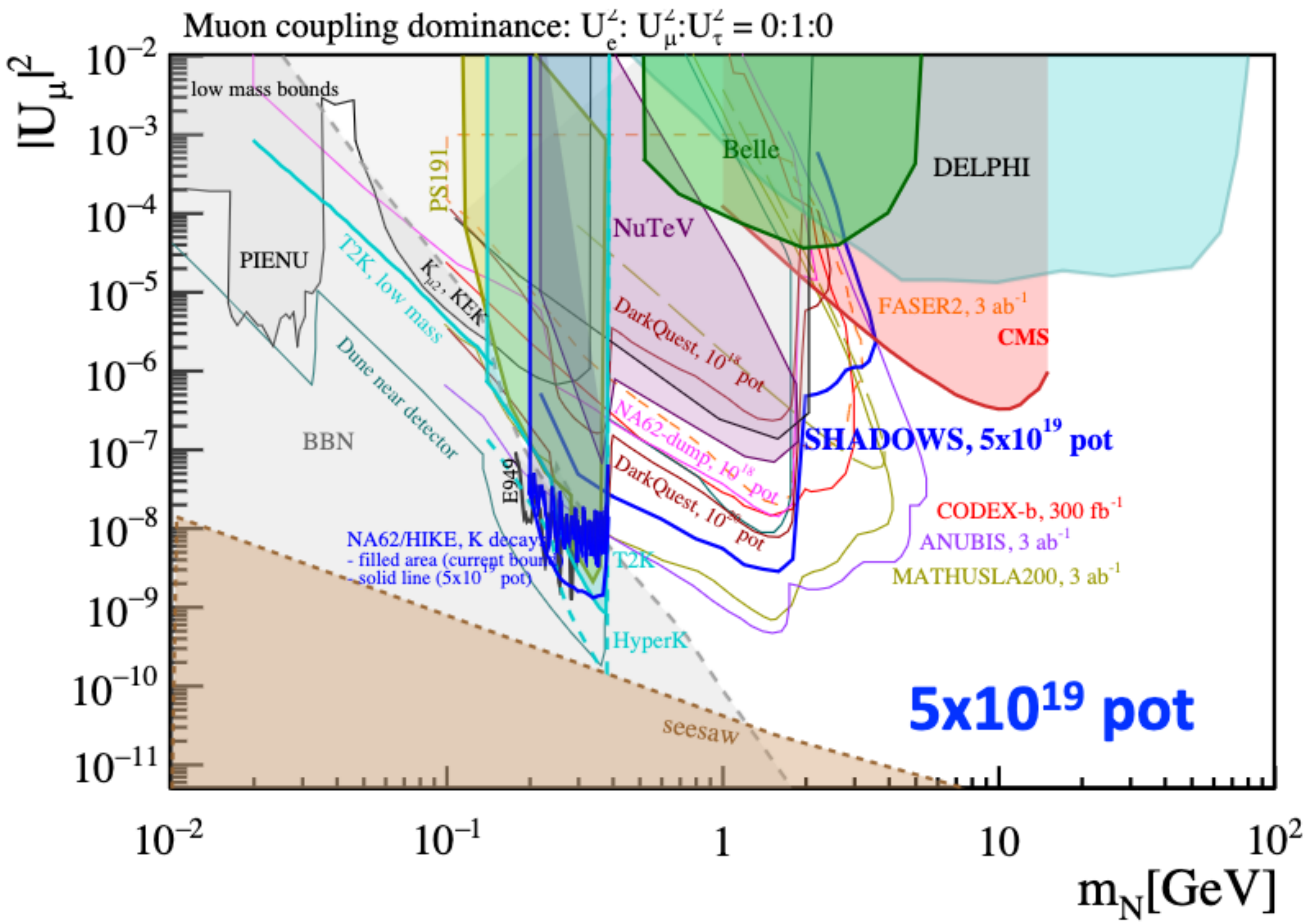
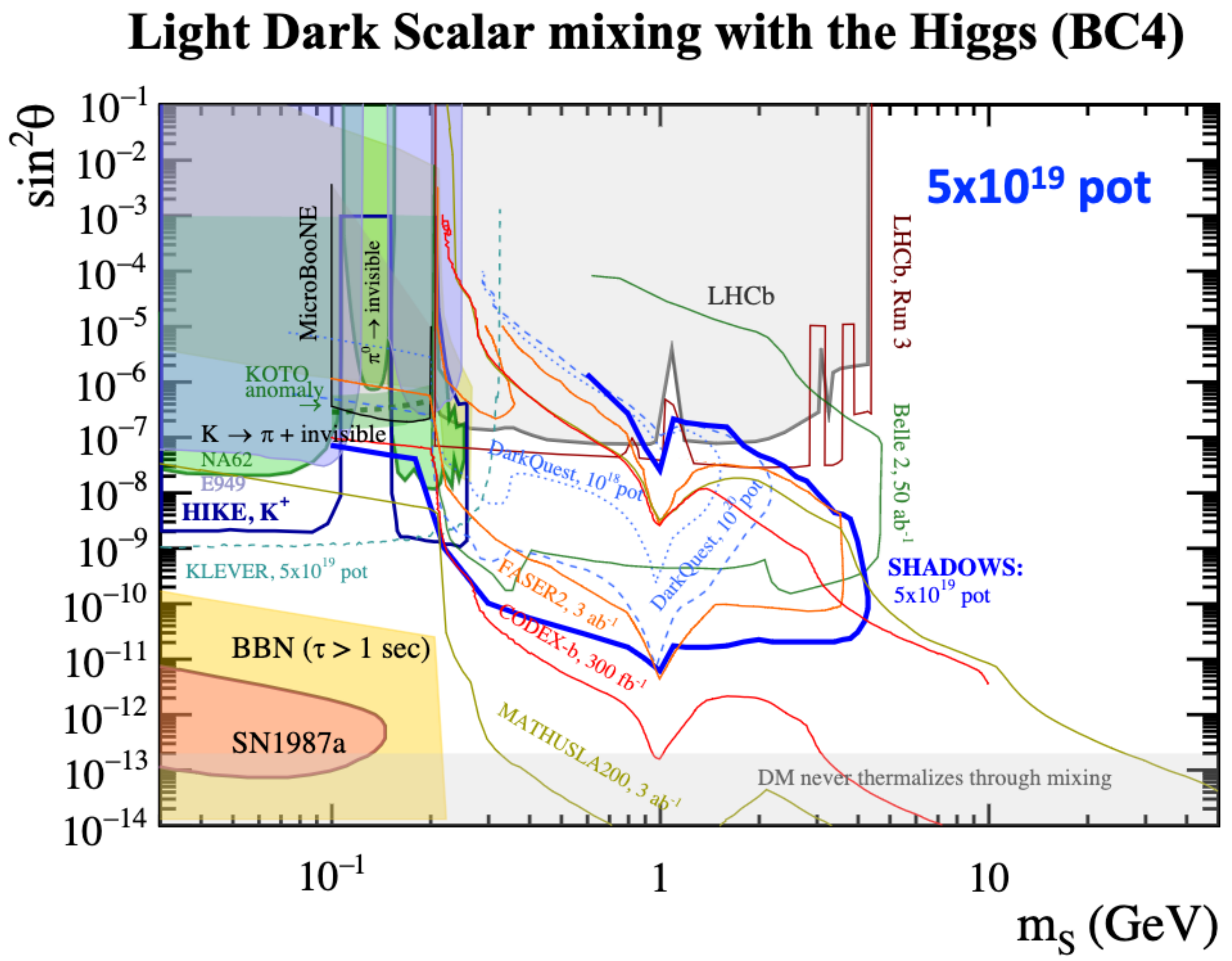
SHADOWS



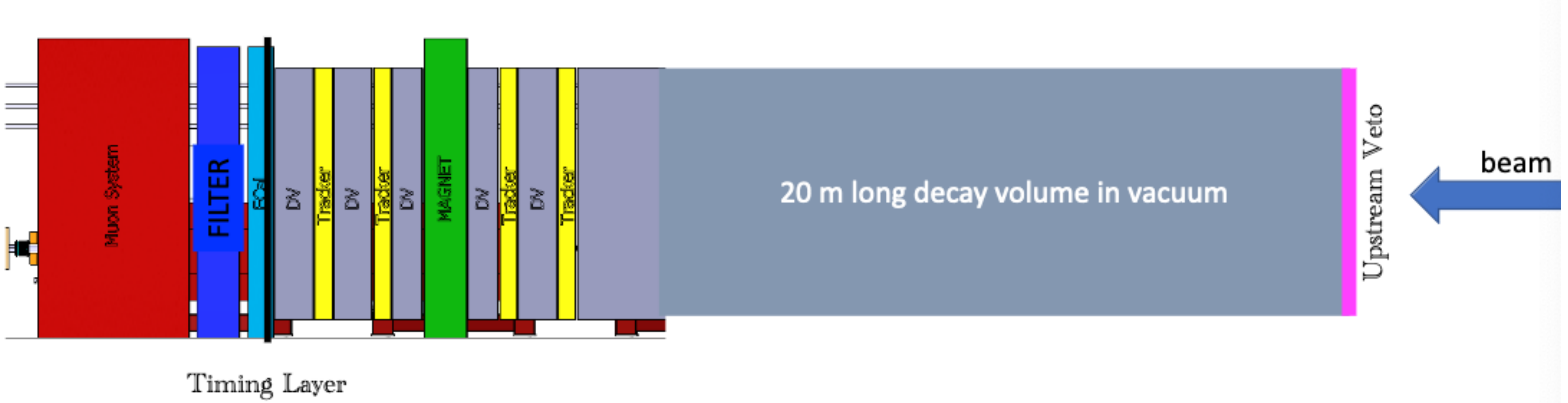
ALPs with fermion couplings (BC10)
5x10^19 pot
BaBar
K+ → π+ + X
B → K + invisible
K+ → π+ + inv (based on E949 data)
HIKE, K+ mode
CHARM
FASER2, 3 ab-1
CODEX-b, 300 fb-1
MATHUSLA200, 3 ab-1
SHADOWS, 5x10^19 pot
BBN constraints
m_ALP [GeV/c²]
g_Y = 2v/f



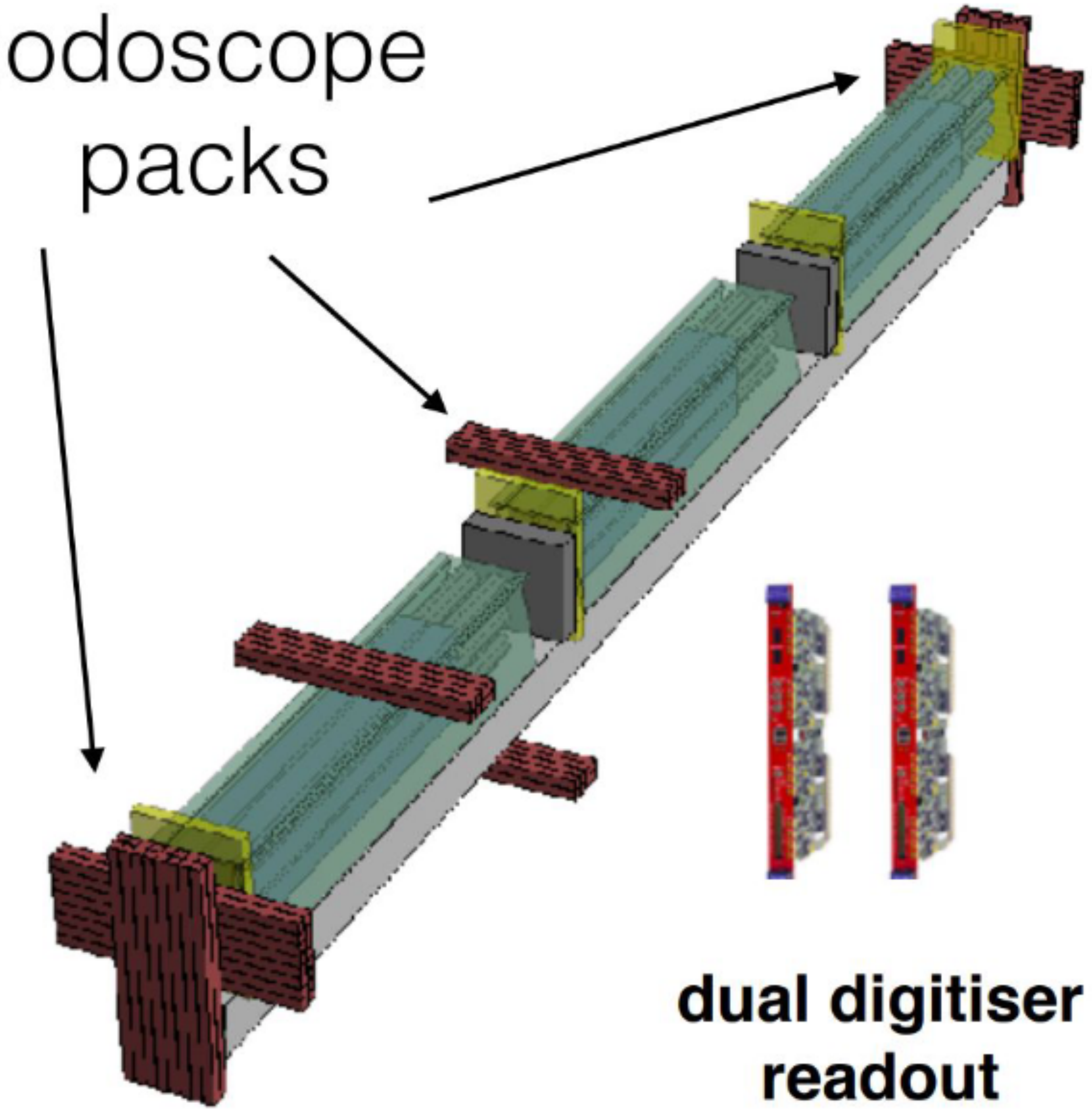
Muon coupling dominance: U²e: U²μ:U²τ = 0:1:0
low mass bounds
PIENU
BBN
NuTeV
Belle
DELPHI
FASER2, 3 ab-1
CMS
SHADOWS, 5x10^19 pot
CODEX-b, 300 fb-1
ANUBIS, 3 ab-1
MATHUSLA200, 3 ab-1
HyperK
T2K
seesaw
5x10^19 pot
m_N[GeV]
|U_μ|²



Light Dark Scalar mixing with the Higgs (BC4)
5x10^19 pot
LHCb
MicroBooNE
KOTO anomaly
K → π + invisible
NA62
E949
HIKE, K+
KLEVER, 5x10^19 pot
SHADOWS: 5x10^19 pot
BBN (τ > 1 sec)
SN1987a
DM never thermalizes through mixing
m_S (GeV)
sin²θ

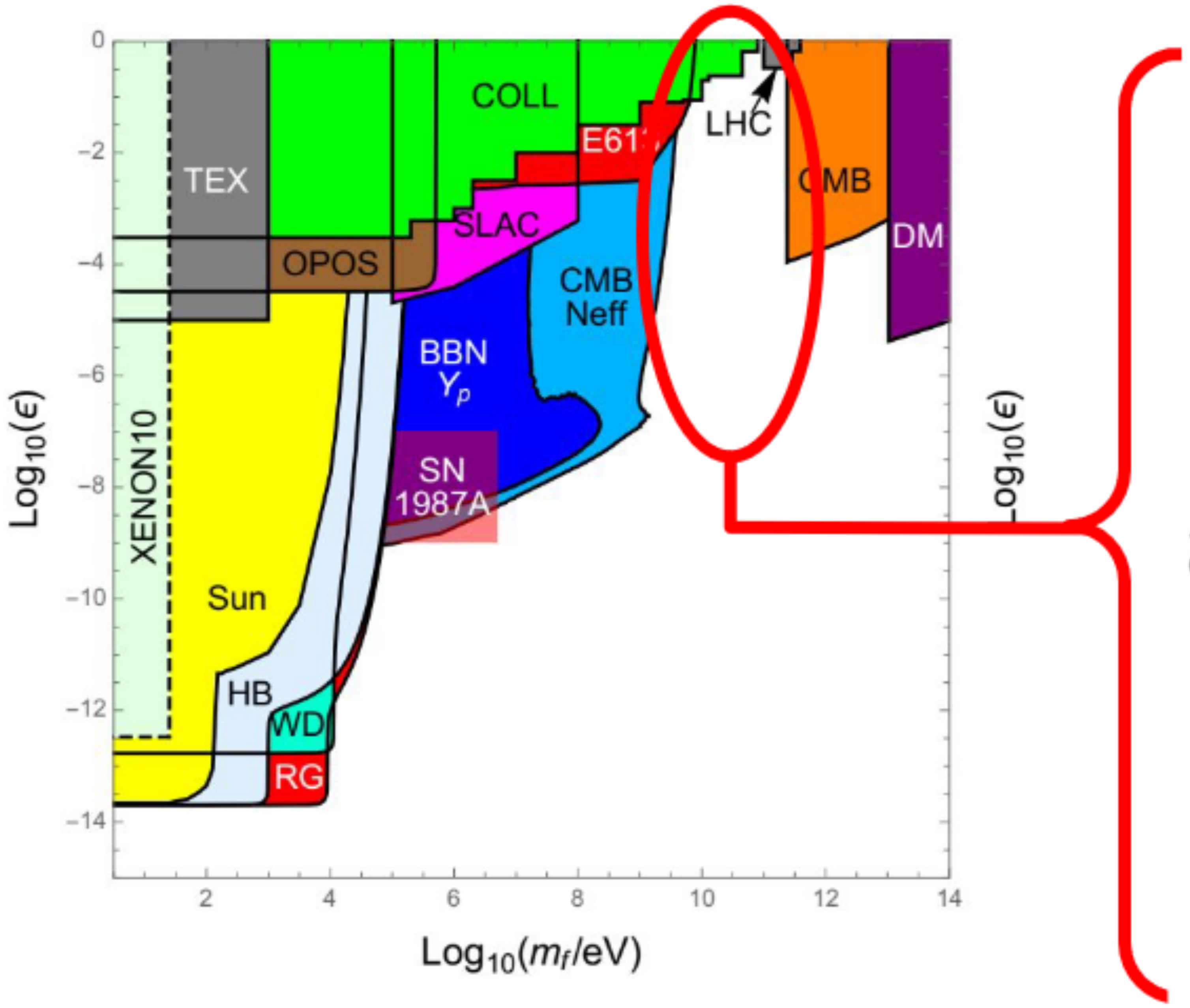


Muon System
FILTER
ECal
DV
Tracker
MAGNET
20 m long decay volume in vacuum
Upstream Veto
beam
Timing Layer

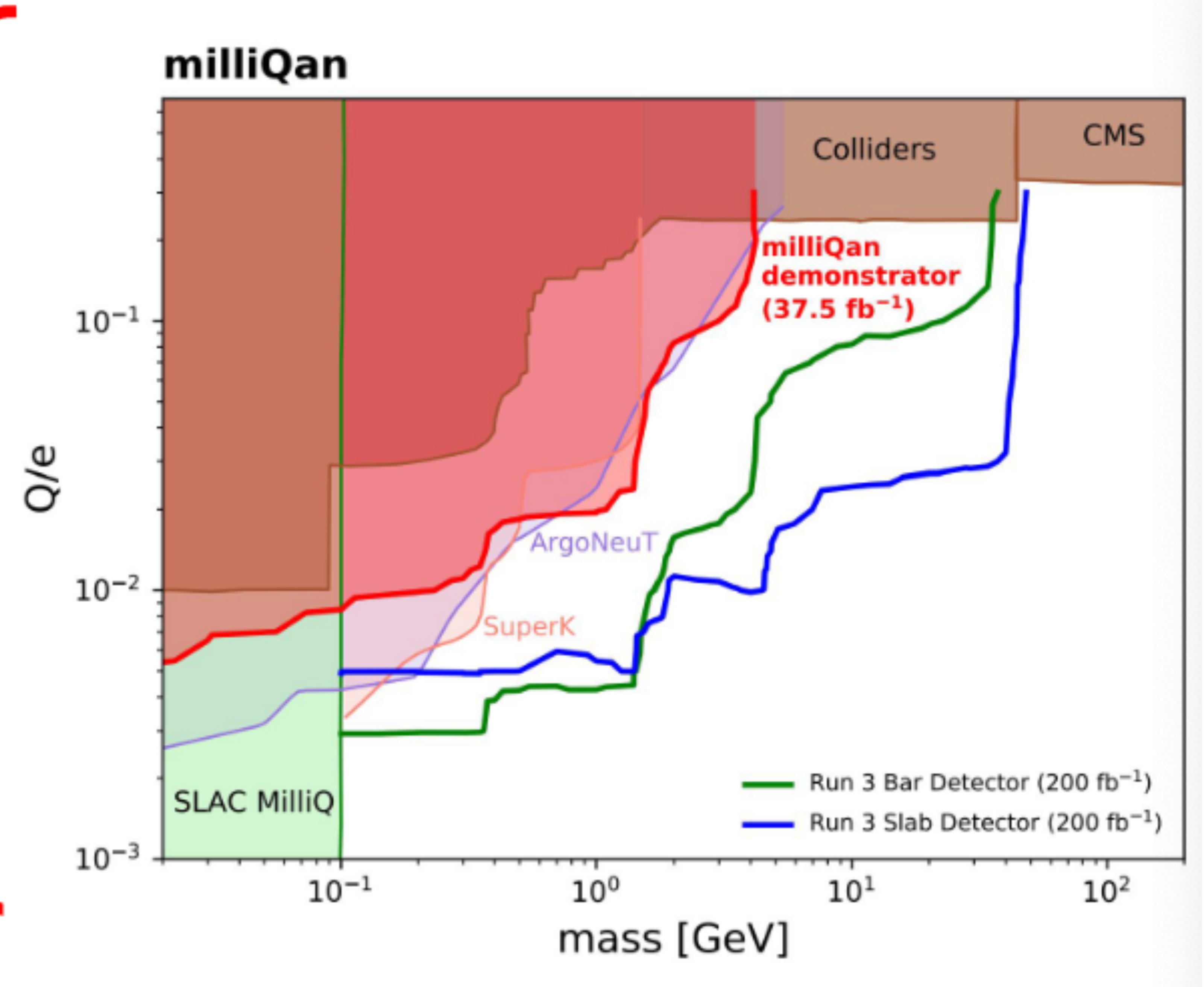


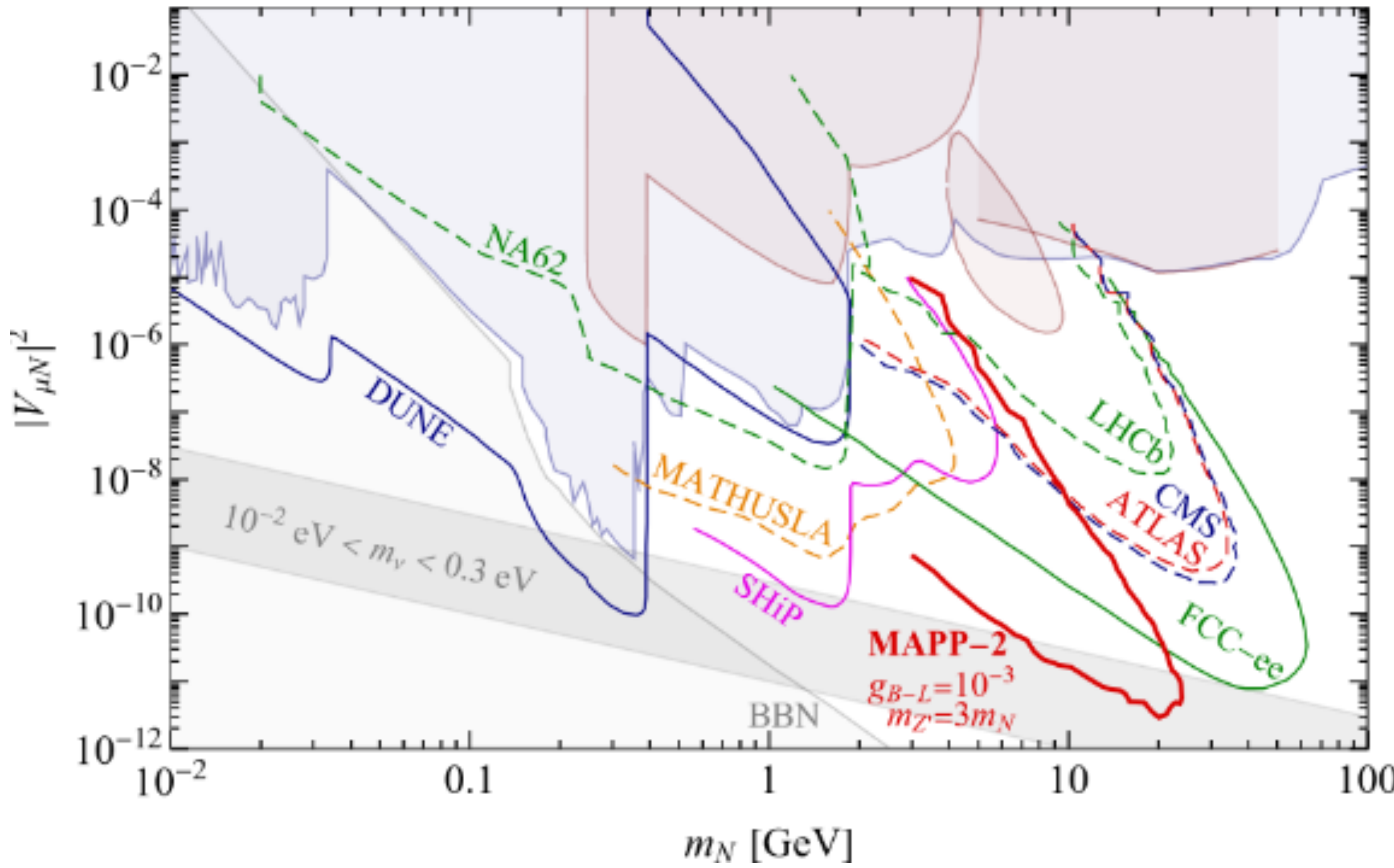
dual digitiser readout

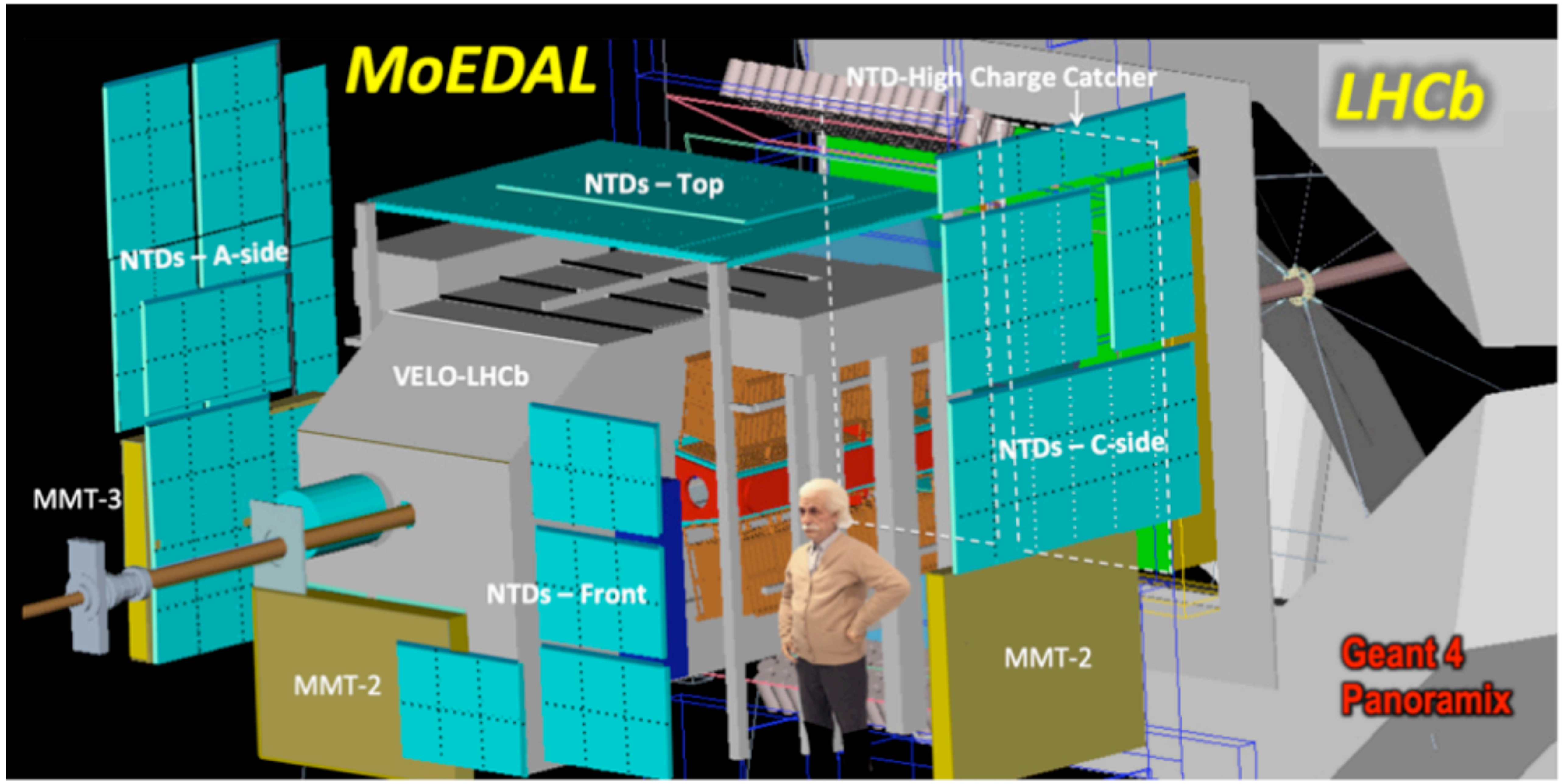
CAEN V1743 digitizer:
16 chan, 1.6 GS/s,
640 ns window

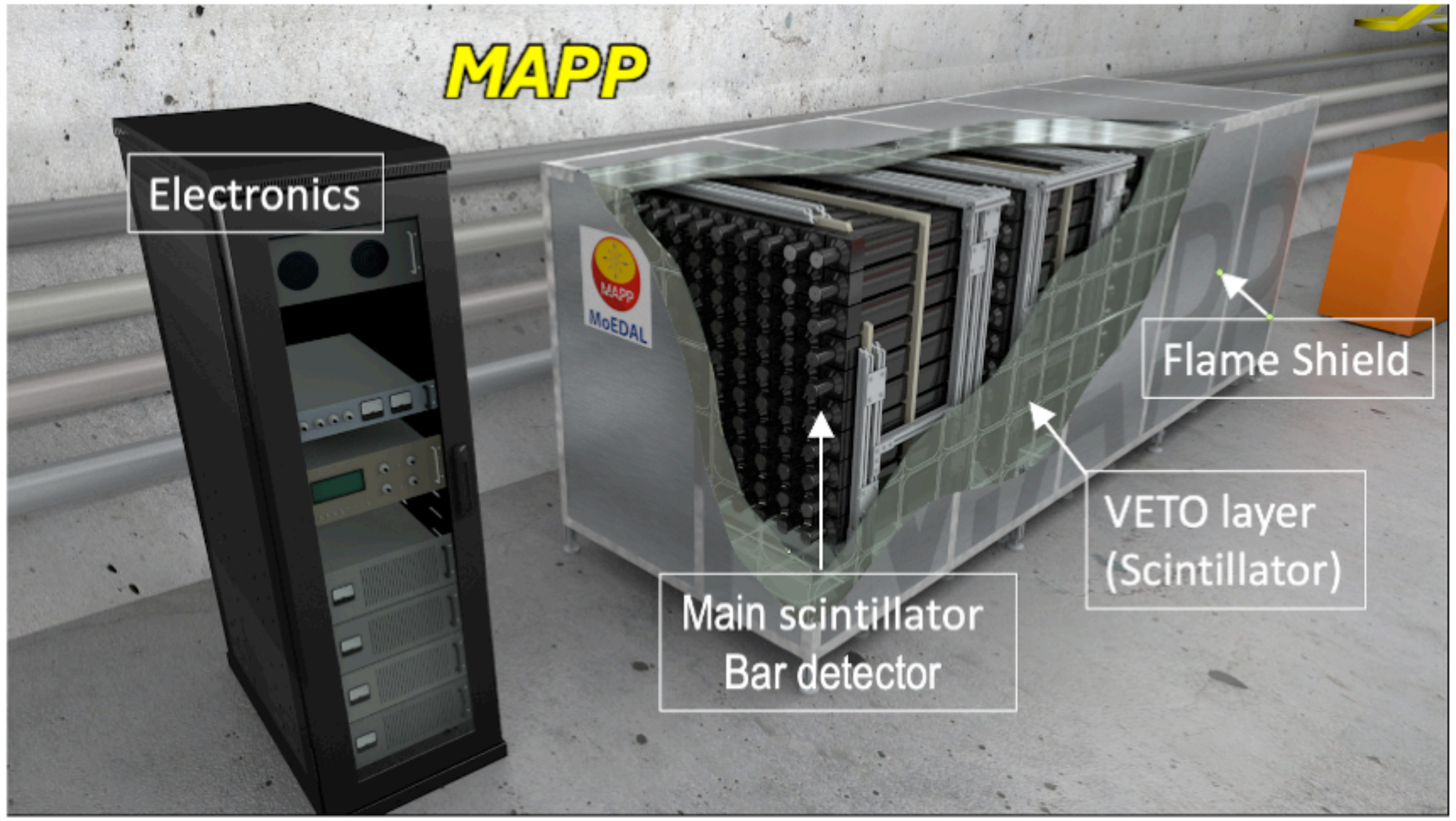


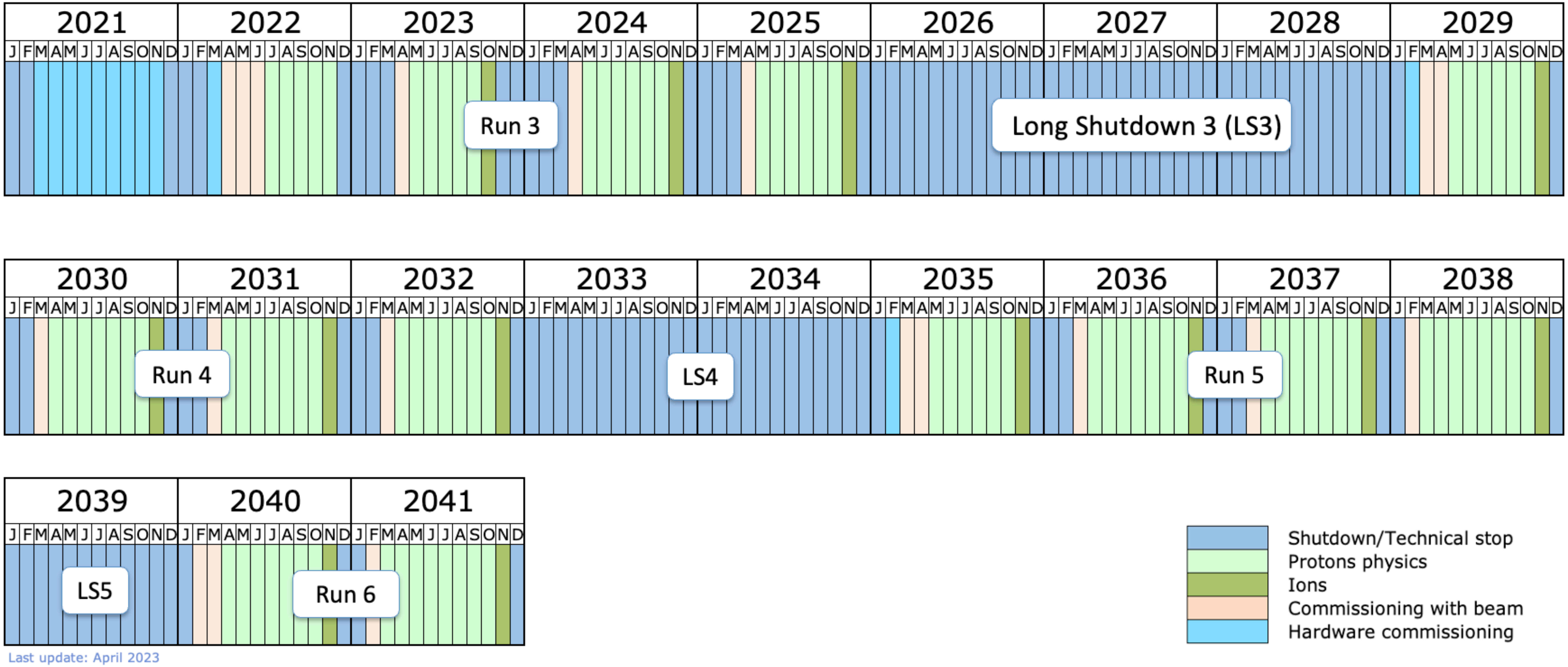
10.1103/PhysRevD.102.032002

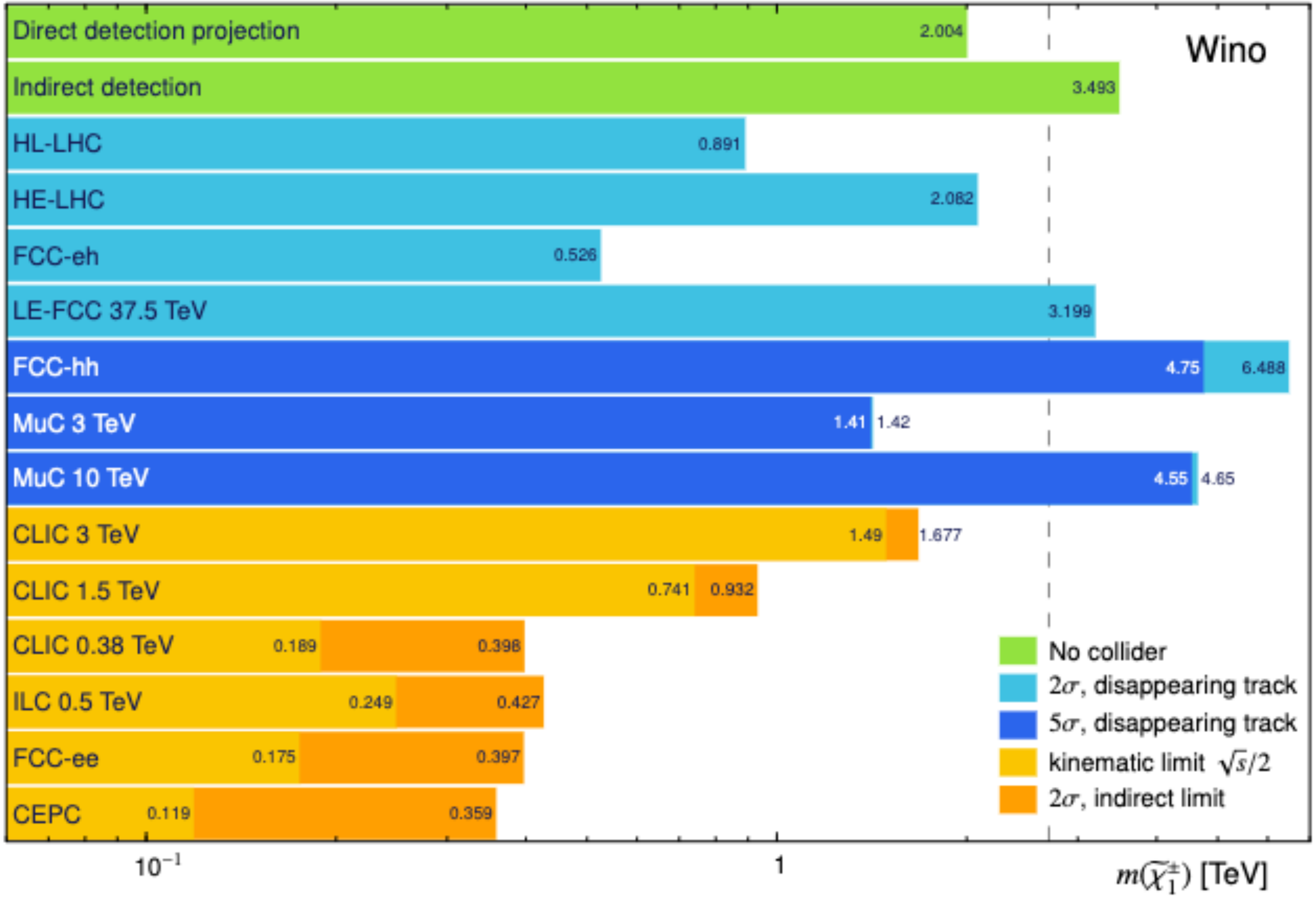


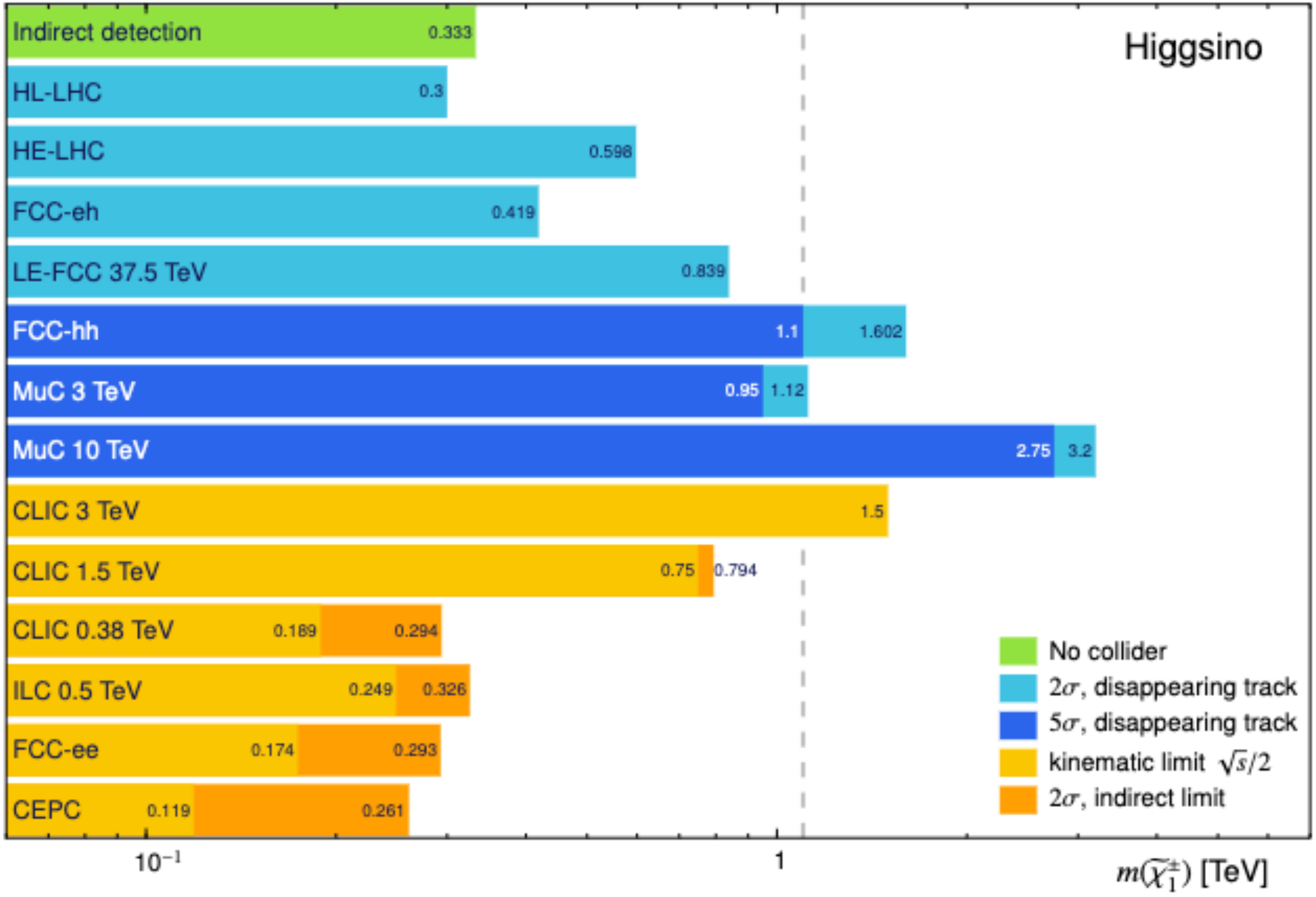

10^{-2}
10^{-4}
10^{-6}
10^{-8}
10^{-10}
10^{-12}
$|V_{\mu N}|^2$
10^{-2}
0.1
1
10
100
m_N [GeV]
NA62
DUNE
MATHUSLA
SHiP
LHCb
CMS
ATLAS
FCC-ee
MAPP−2
$g_{B-L}=10^{-3}$
$m_{Z'}=3m_N$
BBN
10^{-2} eV $< m_\nu <$ 0.3 eV


MoEDAL
LHCb
NTD-High Charge Catcher
NTDs – Top
NTDs – A-side
VELO-LHCb
NTDs – C-side
MMT-3
NTDs – Front
MMT-2
MMT-2
Geant 4
Panoramix


MAPP
Electronics
Flame Shield
VETO layer
(Scintillator)
Main scintillator
Bar detector


2021
2022
2023
2024
2025
2026
2027
2028
2029
Run 3
Long Shutdown 3 (LS3)
2030
2031
2032
2033
2034
2035
2036
2037
2038
Run 4
LS4
Run 5
2039
2040
2041
LS5
Run 6
Shutdown/Technical stop
Protons physics
Ions
Commissioning with beam
Hardware commissioning
Last update: April 2023

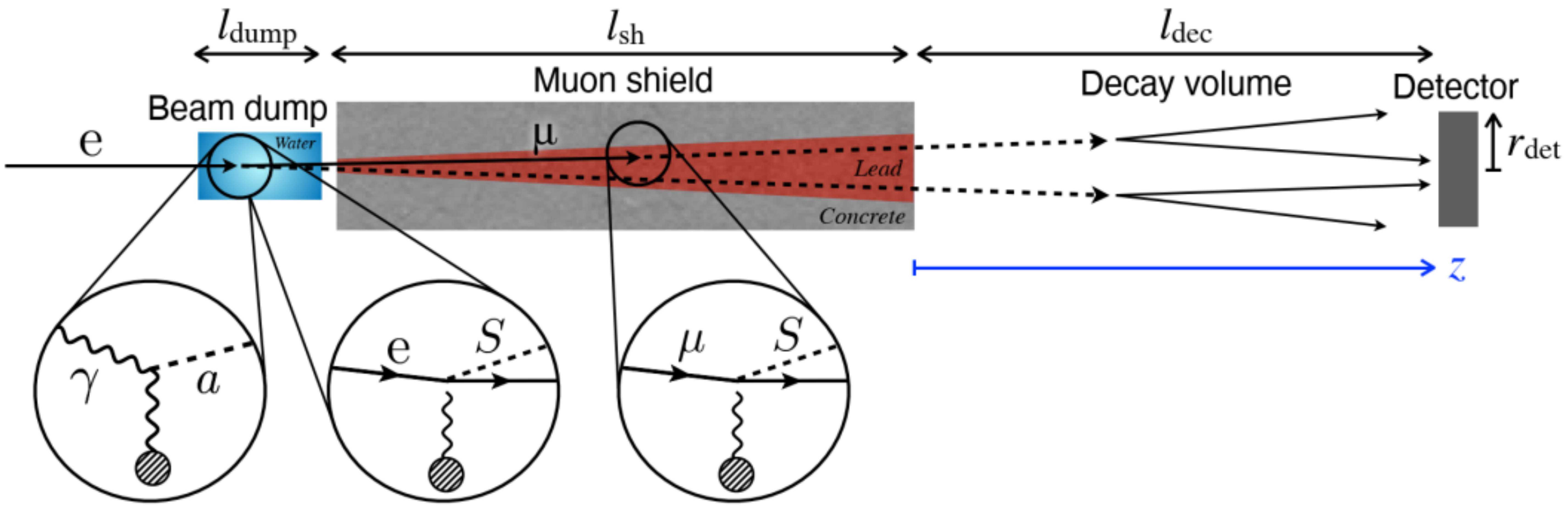

Wino
Direct detection projection
2.004
Indirect detection
3.493
HL-LHC
0.891
HE-LHC
2.082
FCC-eh
0.526
LE-FCC 37.5 TeV
3.199
FCC-hh
4.75
6.488
MuC 3 TeV
1.41
1.42
MuC 10 TeV
4.55
4.65
CLIC 3 TeV
1.49
1.677
CLIC 1.5 TeV
0.741
0.932
CLIC 0.38 TeV
0.189
0.398
ILC 0.5 TeV
0.249
0.427
FCC-ee
0.175
0.397
CEPC
0.119
0.359
No collider
2σ, disappearing track
5σ, disappearing track
kinematic limit √s/2
2σ, indirect limit
10^-1
1
m(χ̃1±) [TeV]



Higgsino
Indirect detection 0.333
HL-LHC 0.3
HE-LHC 0.598
FCC-eh 0.419
LE-FCC 37.5 TeV 0.839
FCC-hh 1.1 1.602
MuC 3 TeV 0.95 1.12
MuC 10 TeV 2.75 3.2
CLIC 3 TeV 1.5
CLIC 1.5 TeV 0.75 0.794
CLIC 0.38 TeV 0.189 0.294
ILC 0.5 TeV 0.249 0.326
FCC-ee 0.174 0.293
CEPC 0.119 0.261
No collider
2σ, disappearing track
5σ, disappearing track
kinematic limit $\sqrt{s}/2$
2σ, indirect limit
10^{-1}
1
$m(\tilde{\chi}_1^\pm)$ [TeV]

Beam dump experiments at linear colliders

- General scheme of an experiment searching for axion-like particles, new scalars or dark photons



- One can look for visible products of LLPs decays (like a →γγ, S→ℓℓ) or for secondary interactions of invisible decay products in dedicated far detector (like in direct DM detection experiments; approach used in SLAC Beam Dump Experiment E137: arXiv:1406.2698)

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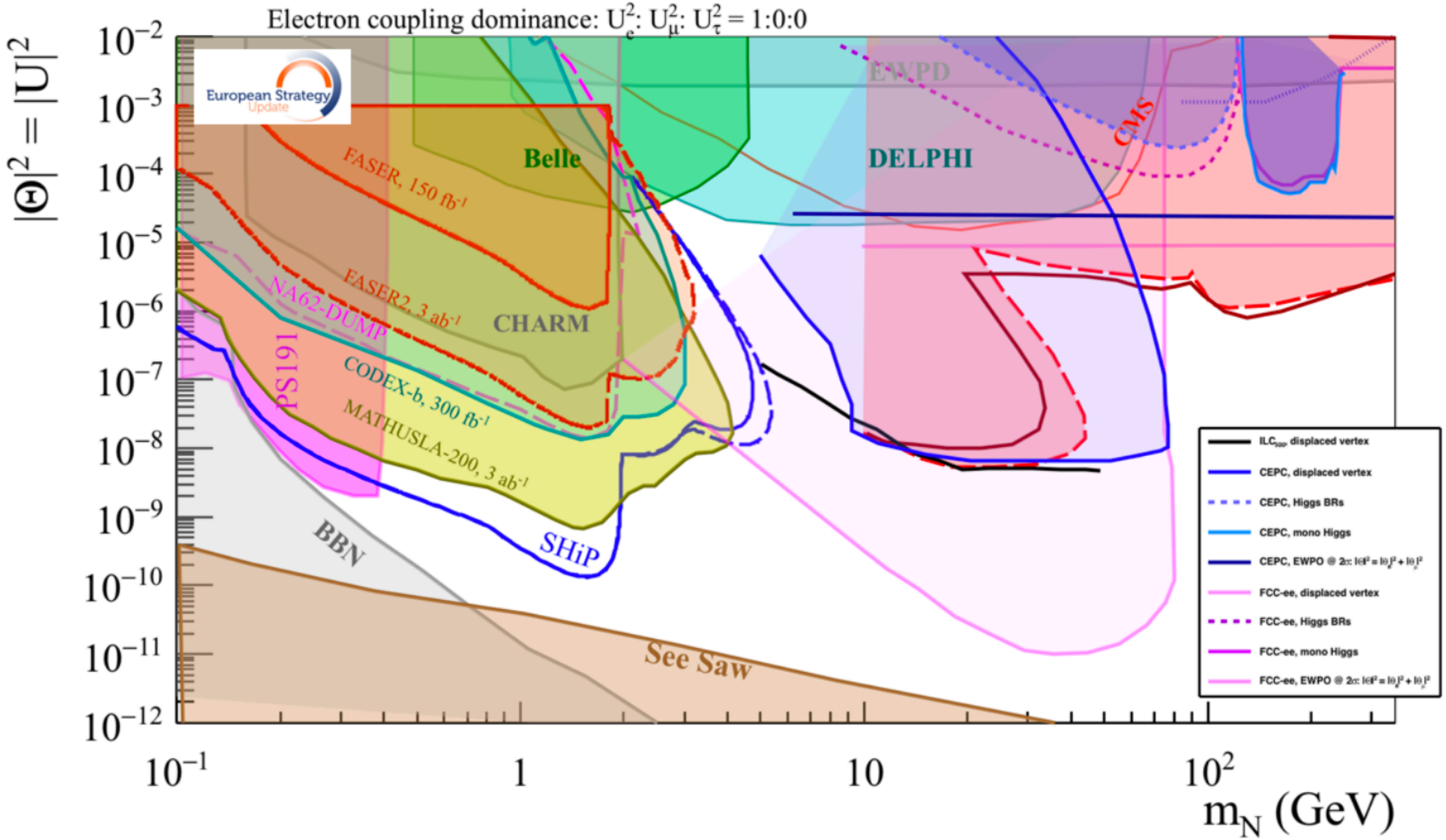
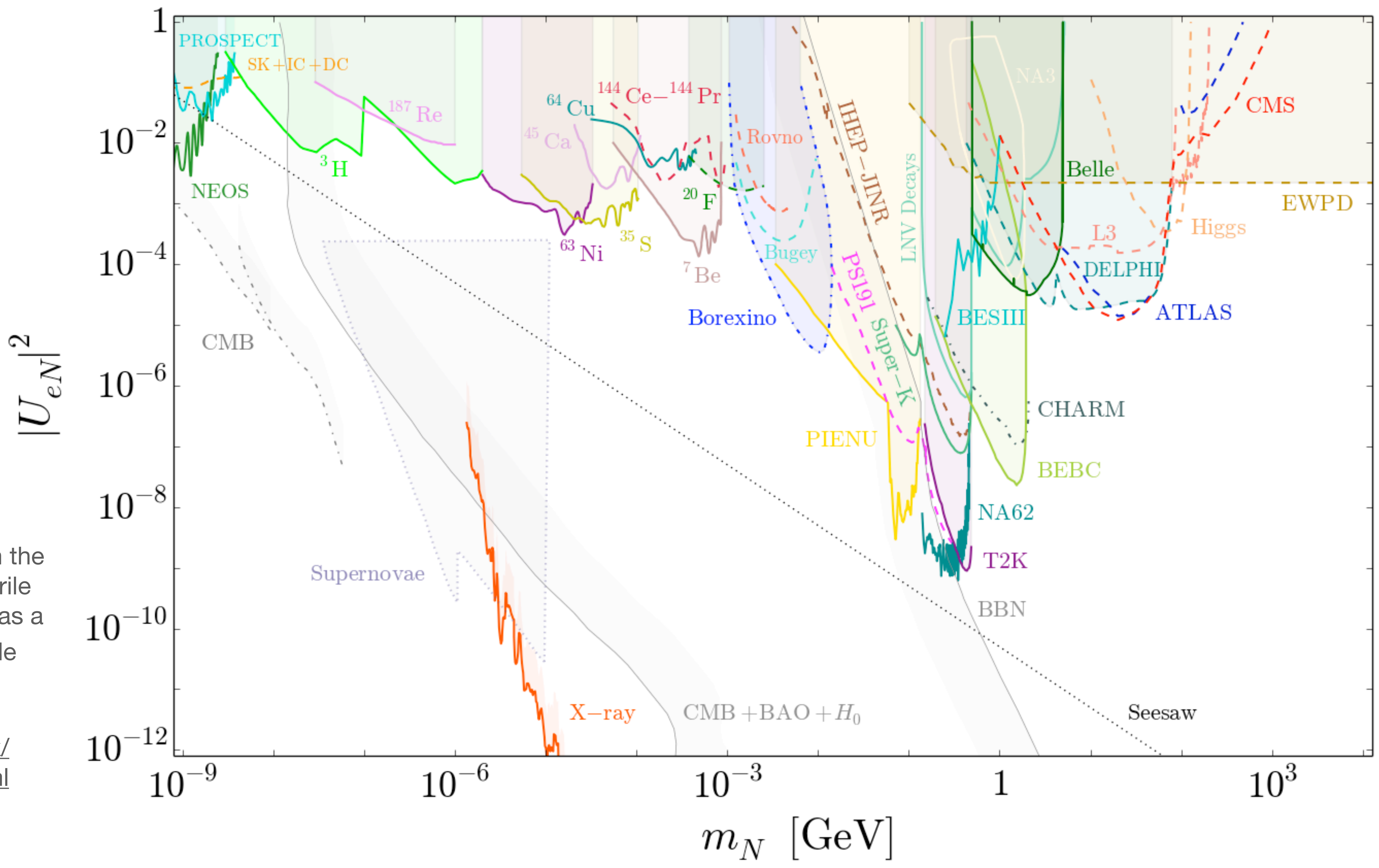
FCC
SUISSE
FRANCE
Genève
Annecy
LHC



90% CL exclusion limits for a HNL mixed with the electron neutrino, from the Physics Briefing Book : Input for the European Strategy for Particle Physics Update 2020 (https://cds.cern.ch/record/2691414/)



Current constraints on the electron neutrino-sterile neutrino mixing $|U_{eN}|^2$ as a function of the sterile neutrino mass m_N https://www.hep.ucl.ac.uk/~pbolton/plots.html

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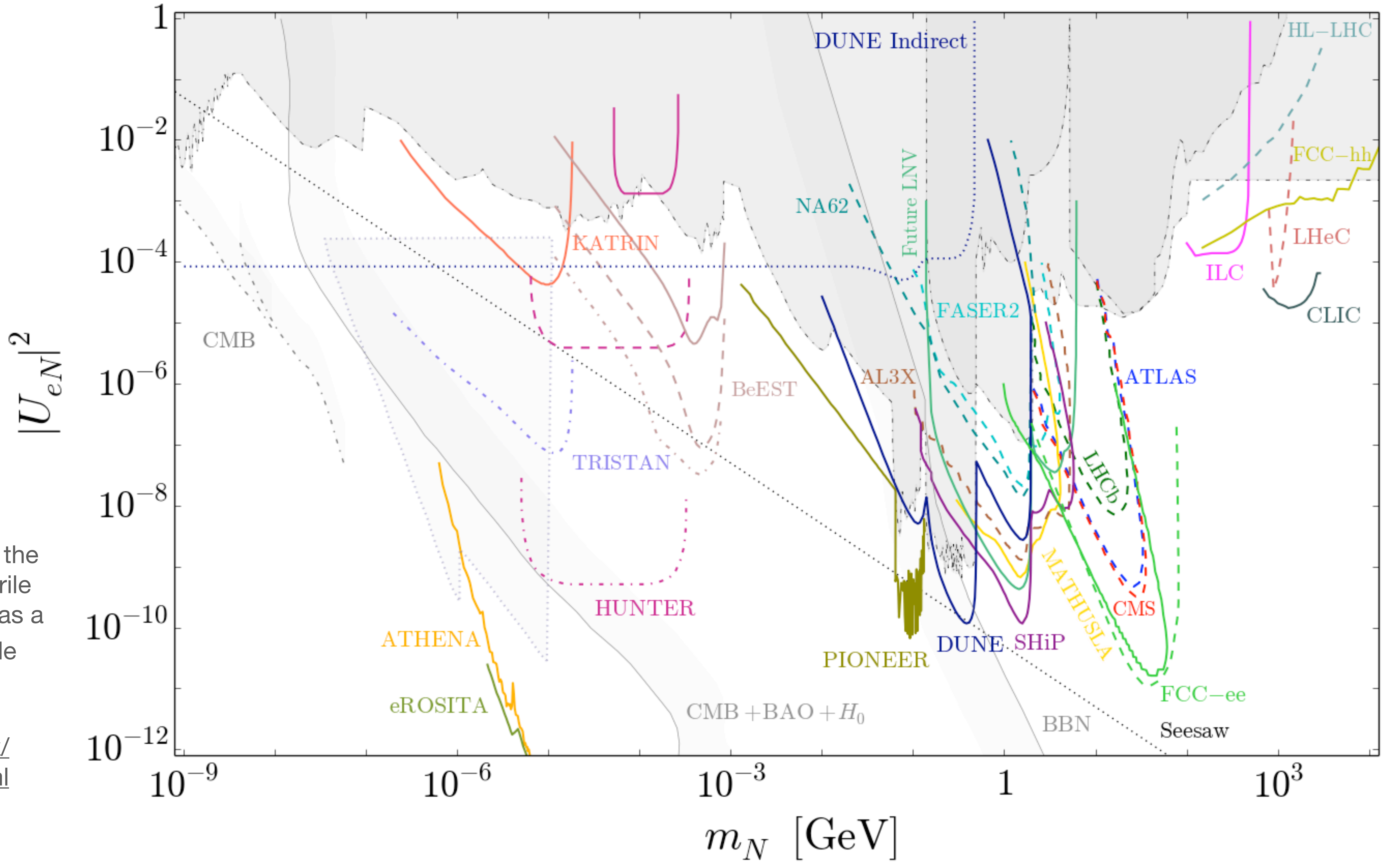
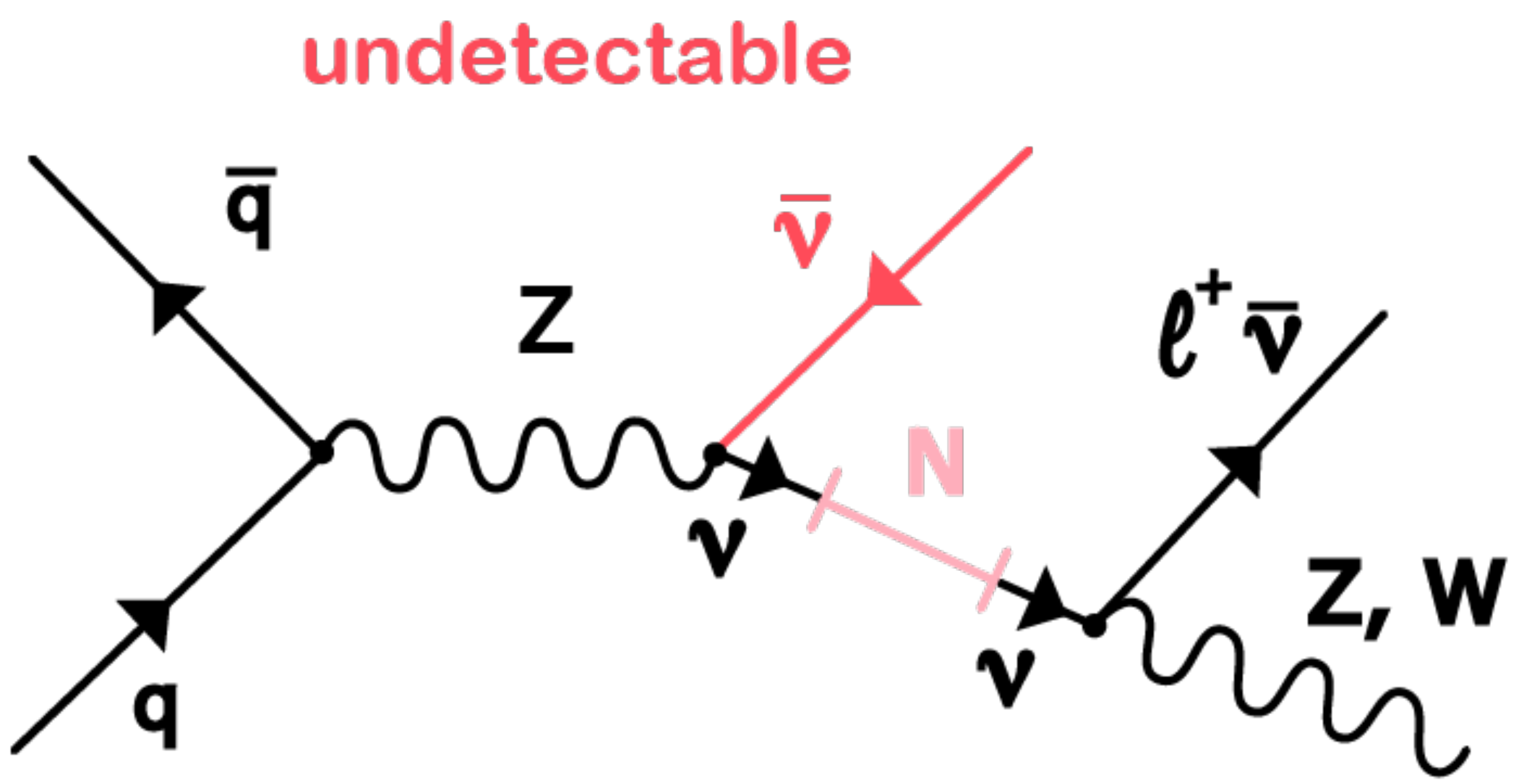
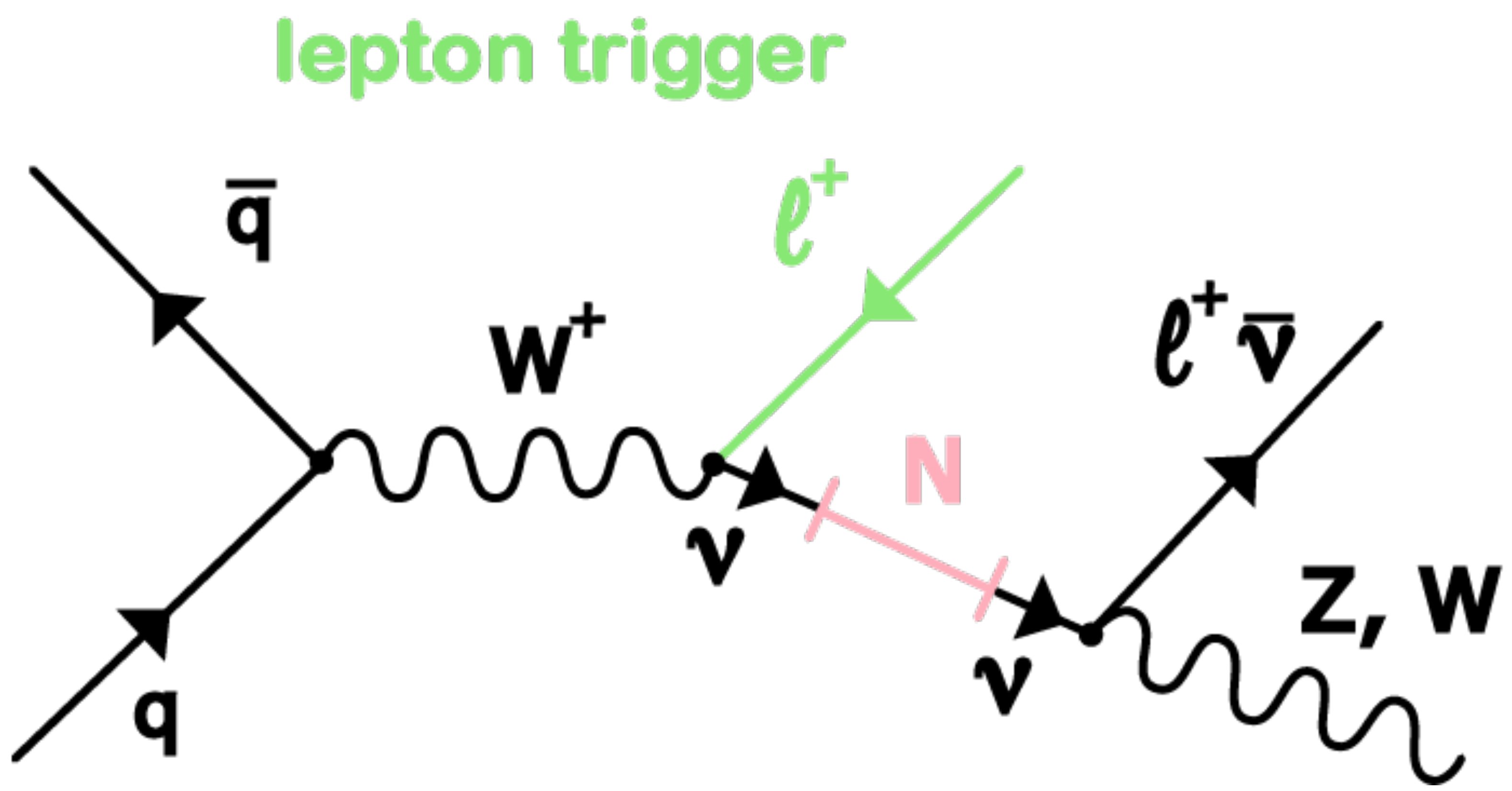


Future constraints on the electron neutrino-sterile neutrino mixing $|U_{eN}|^2$ as a function of the sterile neutrino mass m_N

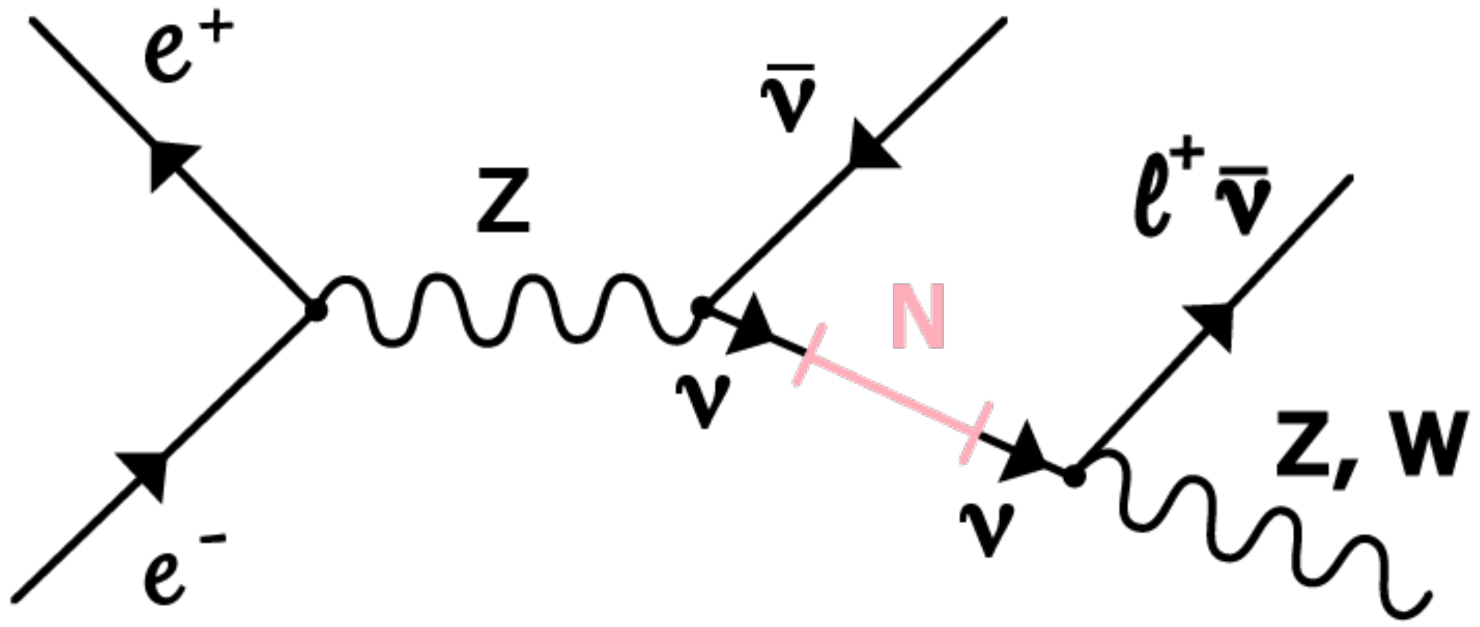
https://www.hep.ucl.ac.uk/~pbolton/plots.html

LHC
(Hadron colliders)
Trigger critical



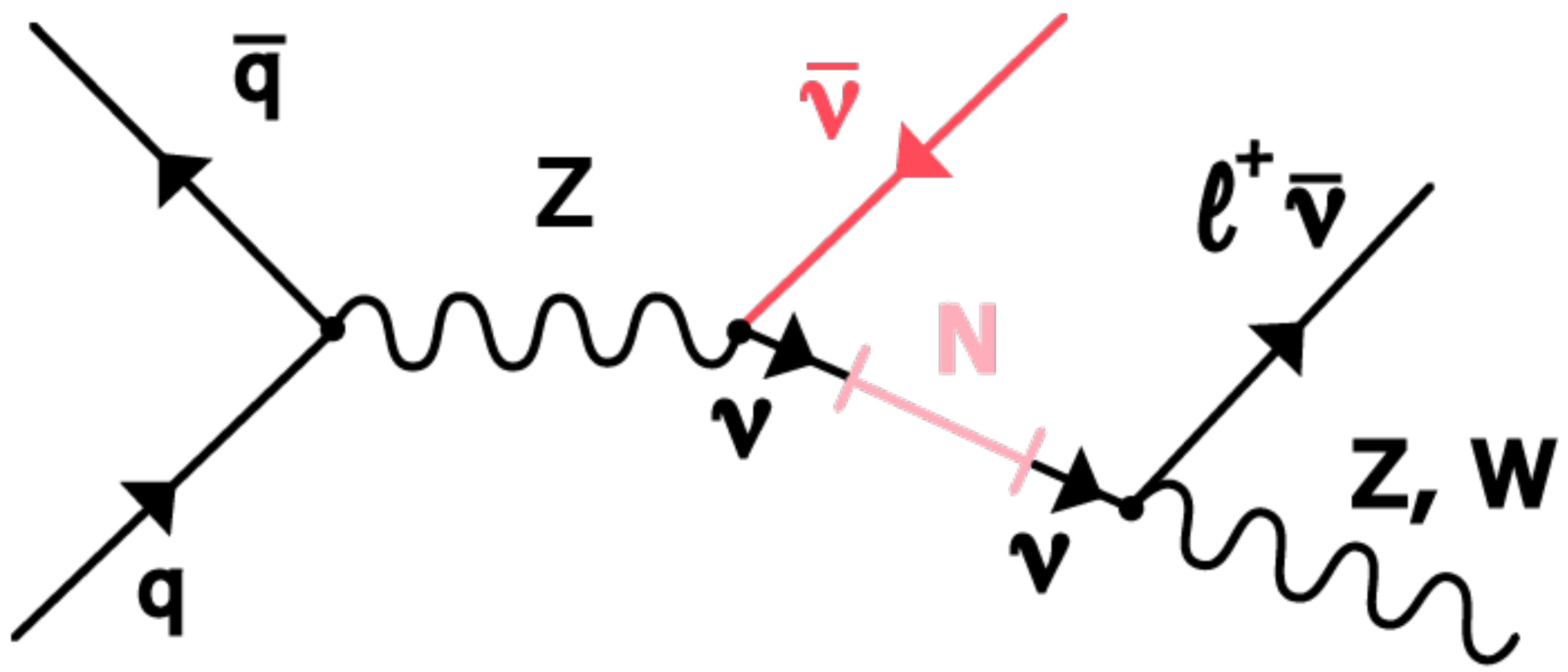


Future lepton collider at Z pole
(FCC-ee)
Much cleaner environment

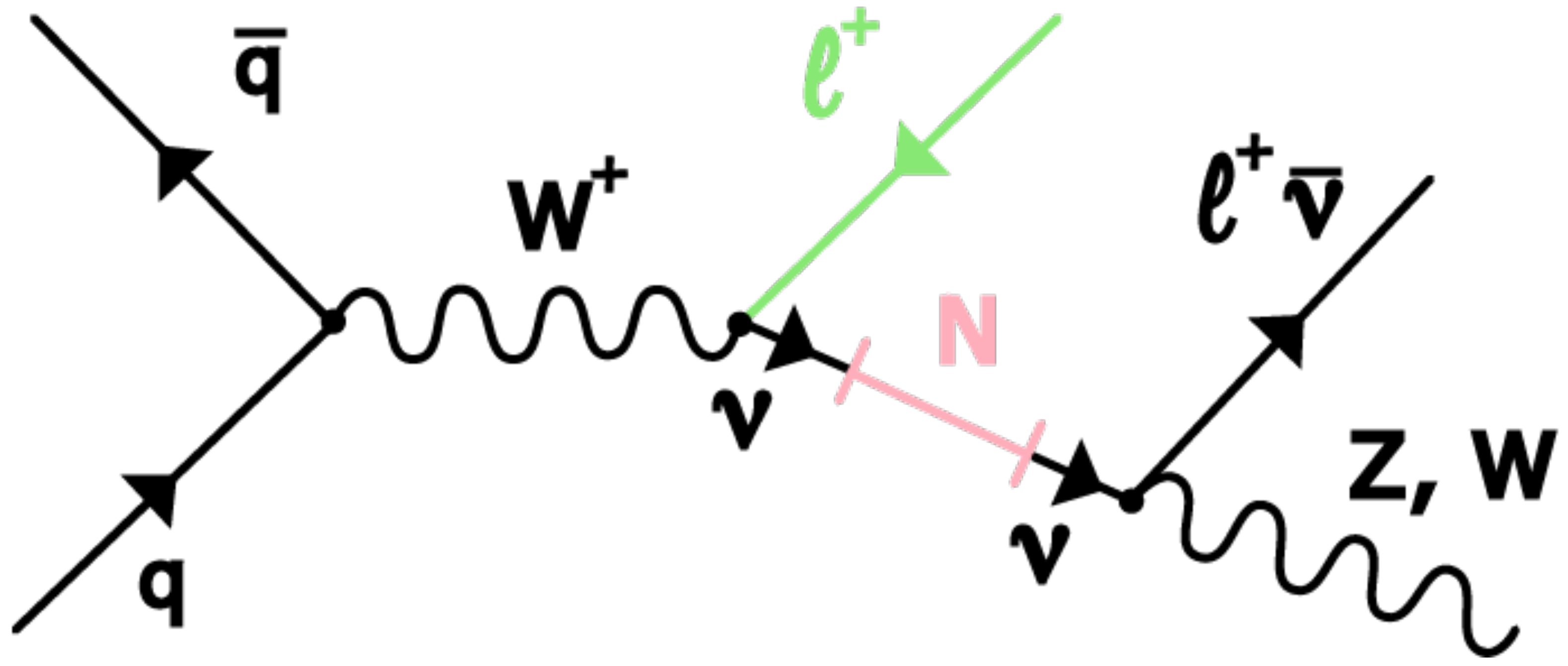


LHC
(Hadron colliders)
Trigger critical

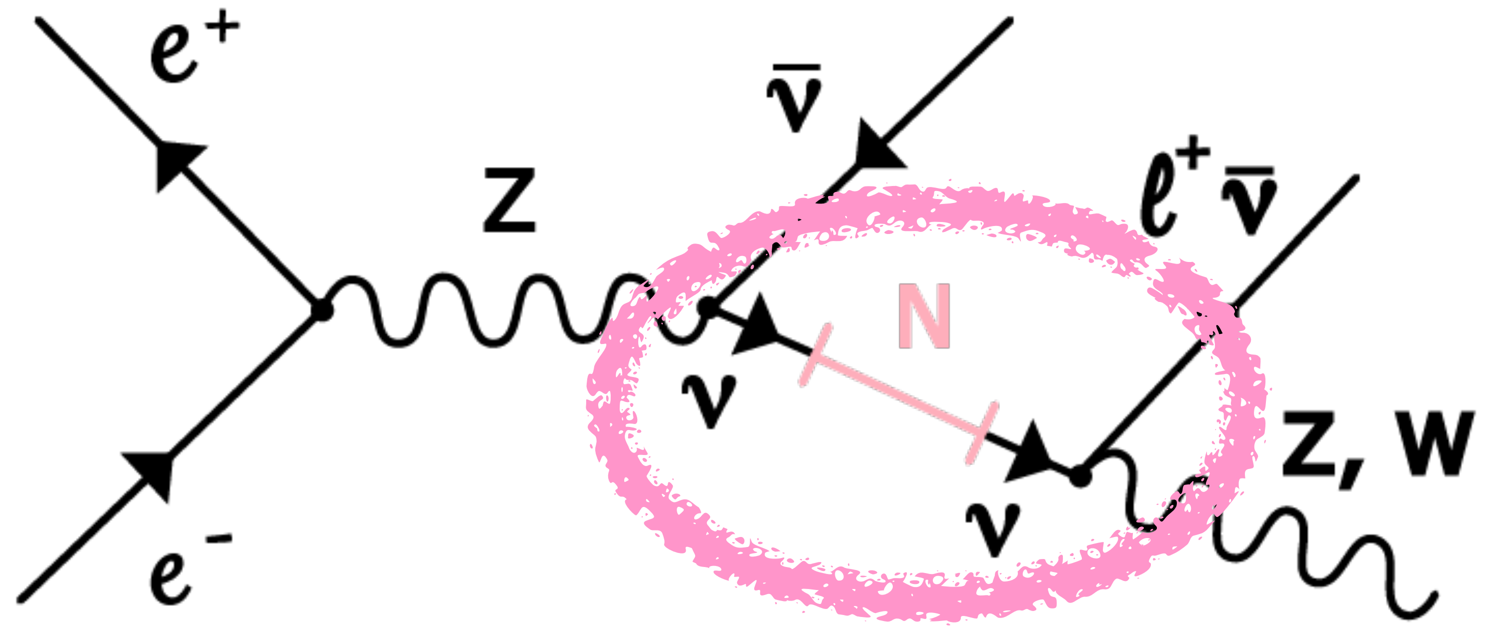
undetectable



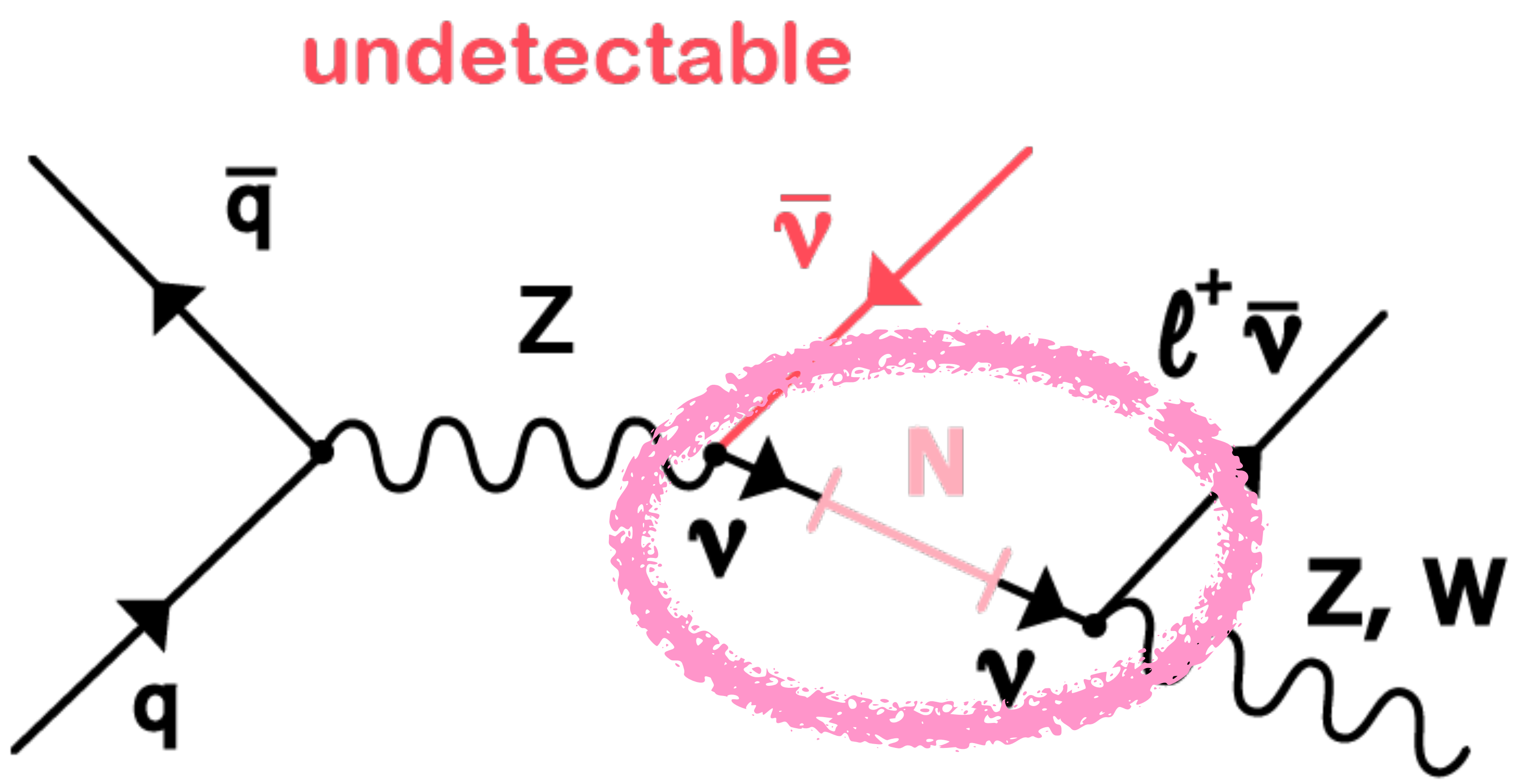
lepton trigger

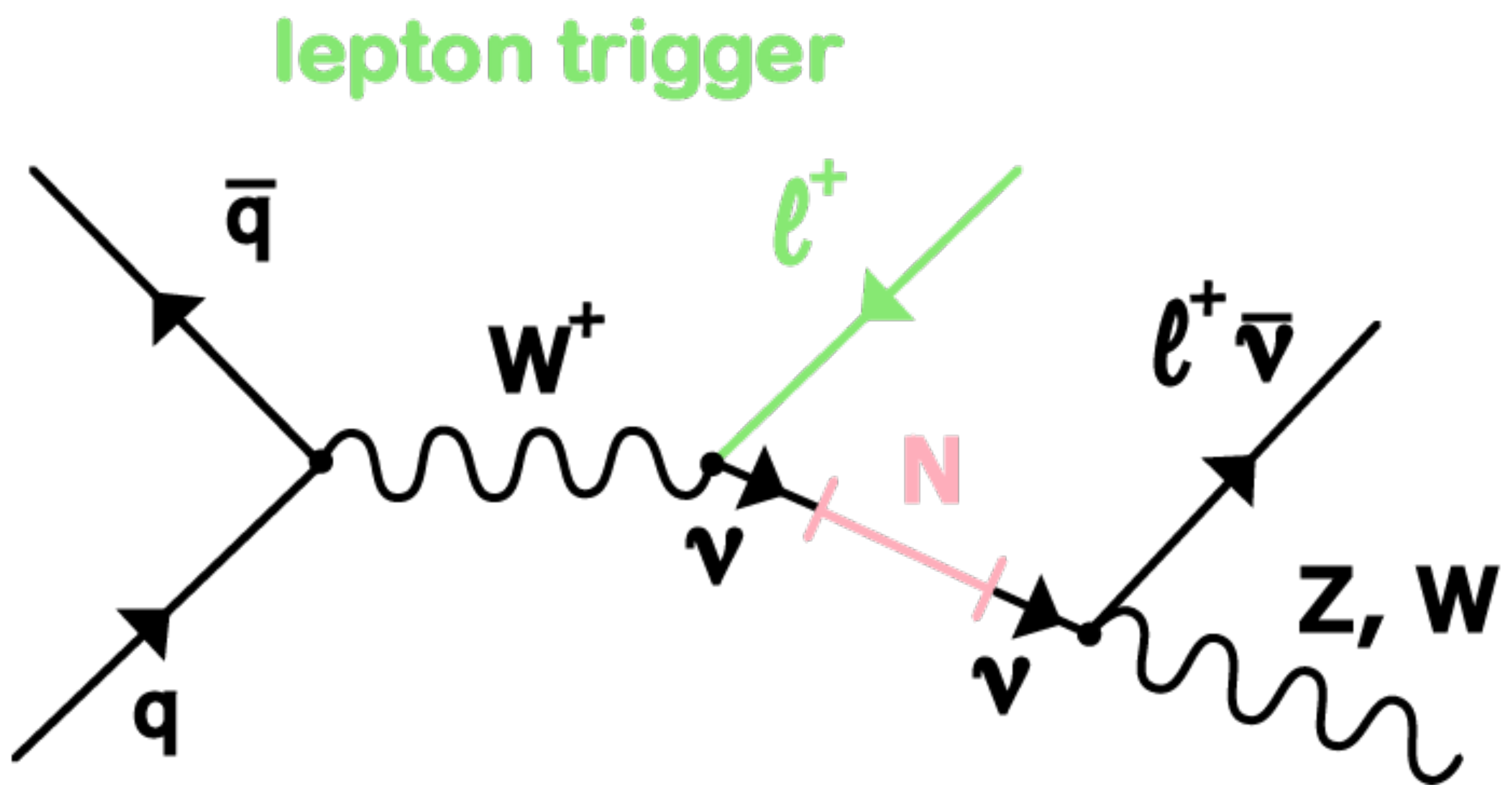


Future lepton collider at Z pole
(FCC-ee)
Much cleaner environment

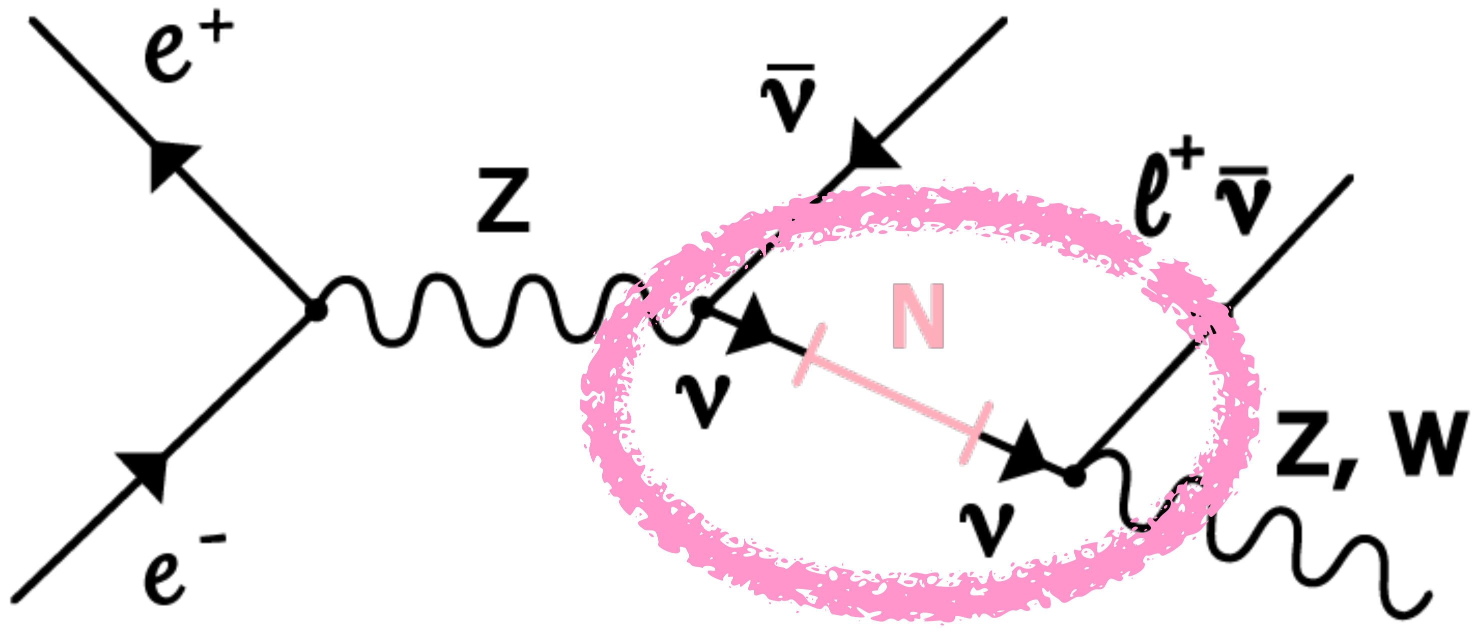


LHC
(Hadron colliders)
Trigger critical





Future lepton collider at Z pole
(FCC-ee)
Much cleaner environment



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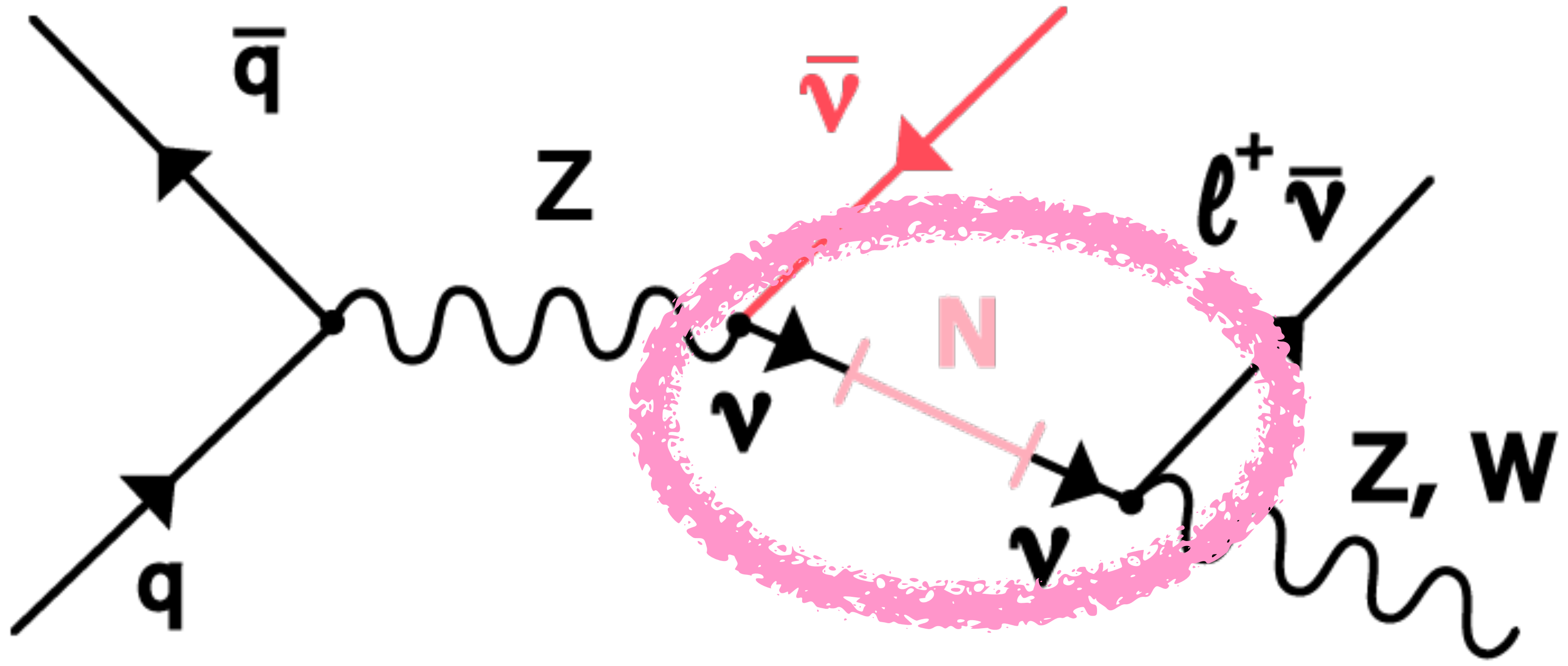
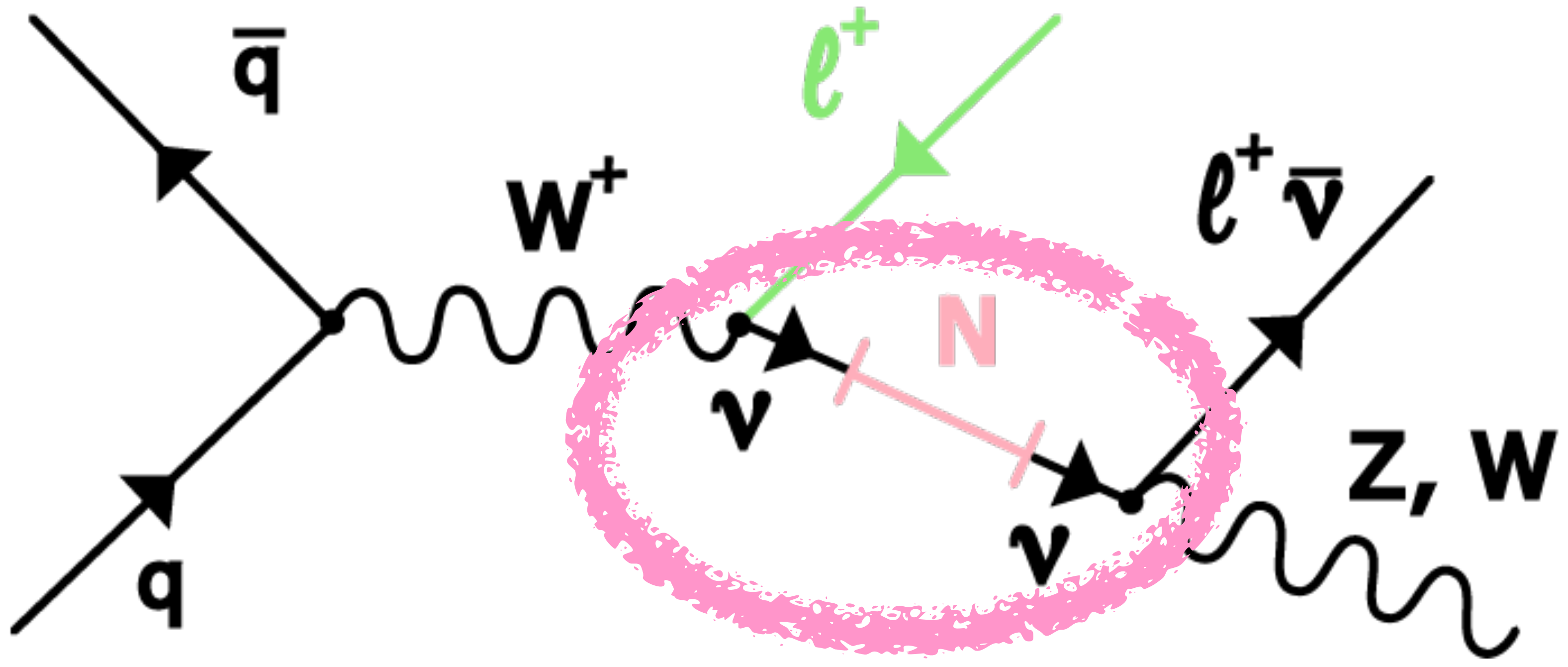
LHC
(Hadron colliders)
Trigger critical

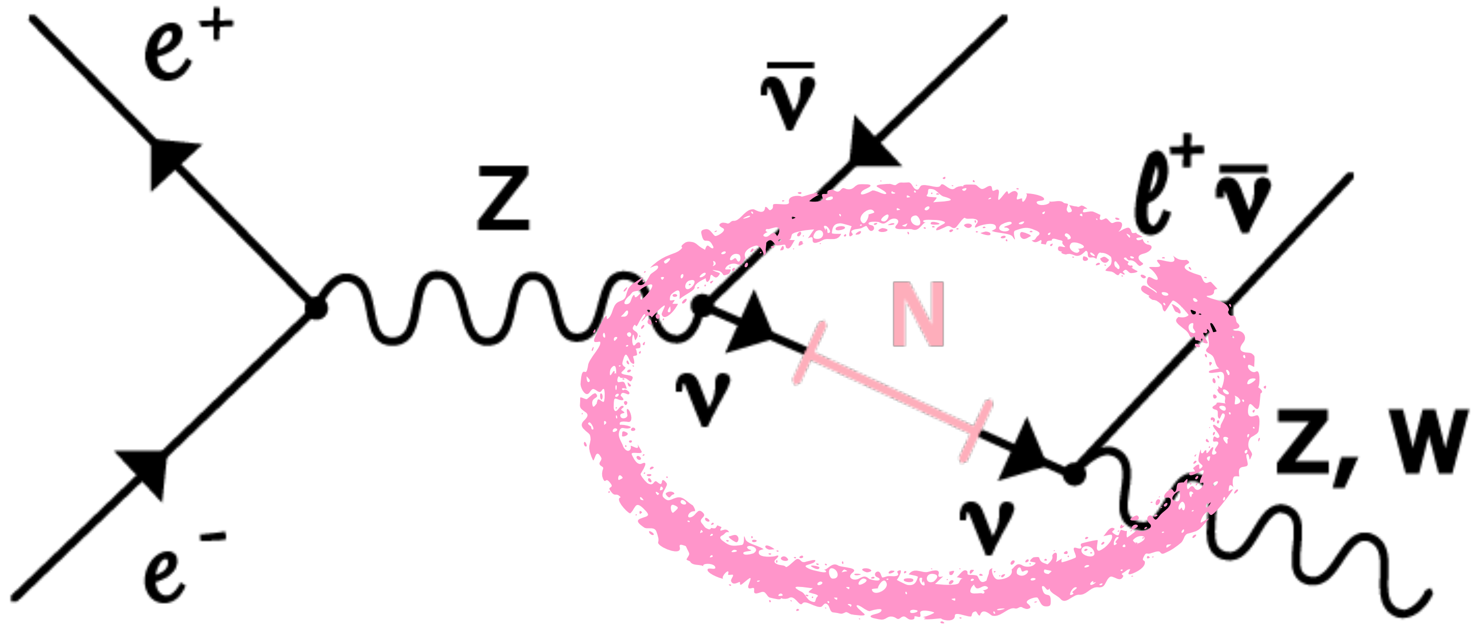
undetectable



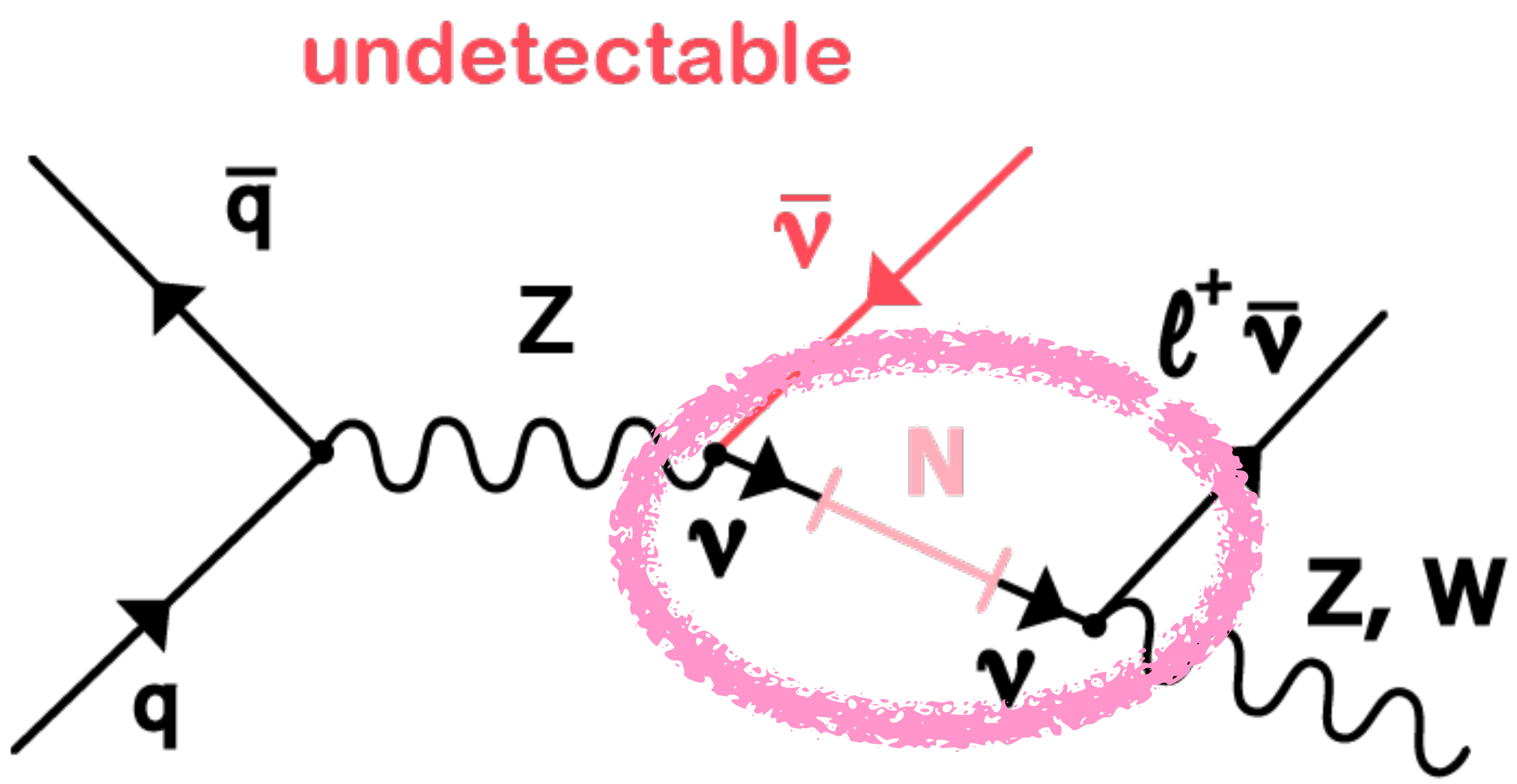
lepton trigger

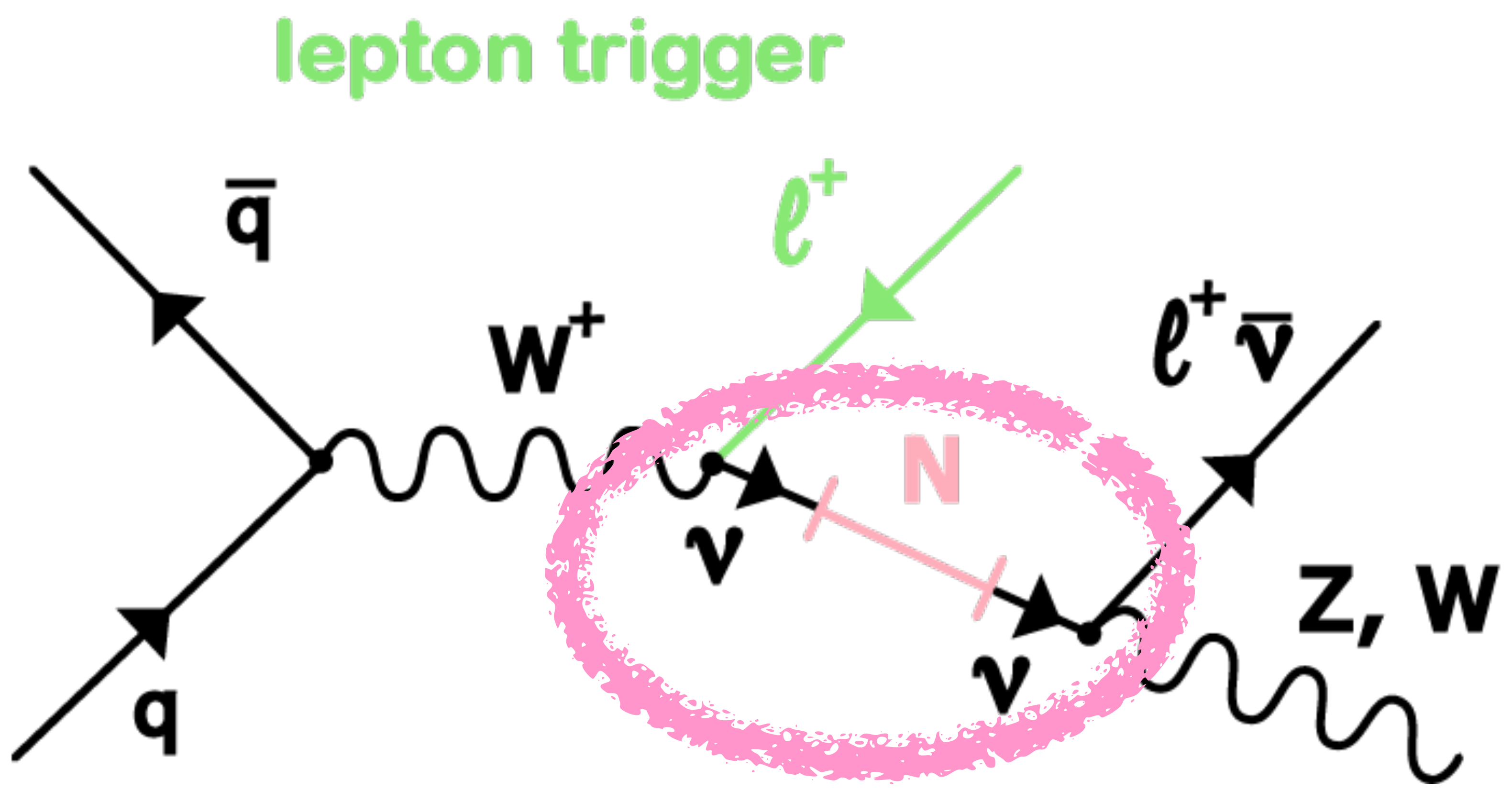


Future lepton collider
at Z pole
(FCC-ee)
Much cleaner
environment

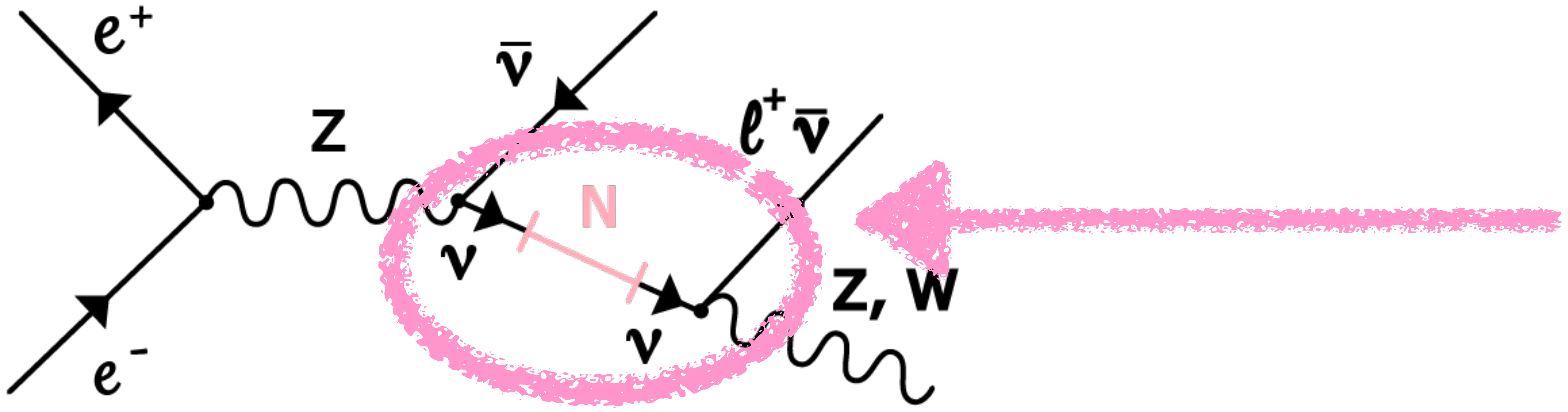


LHC
(Hadron colliders)
Trigger critical



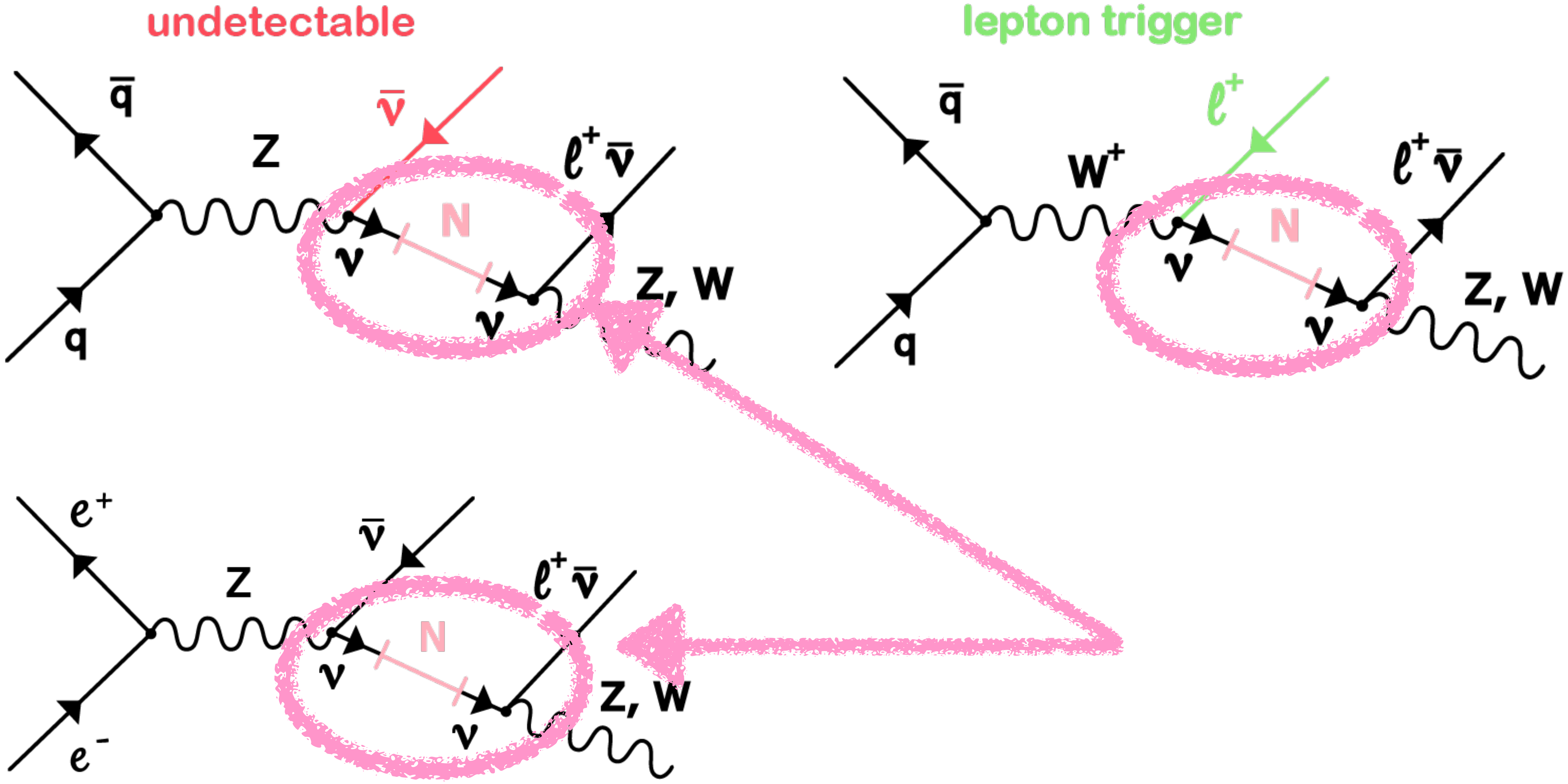


Future lepton collider at Z pole
(FCC-ee)
Much cleaner environment



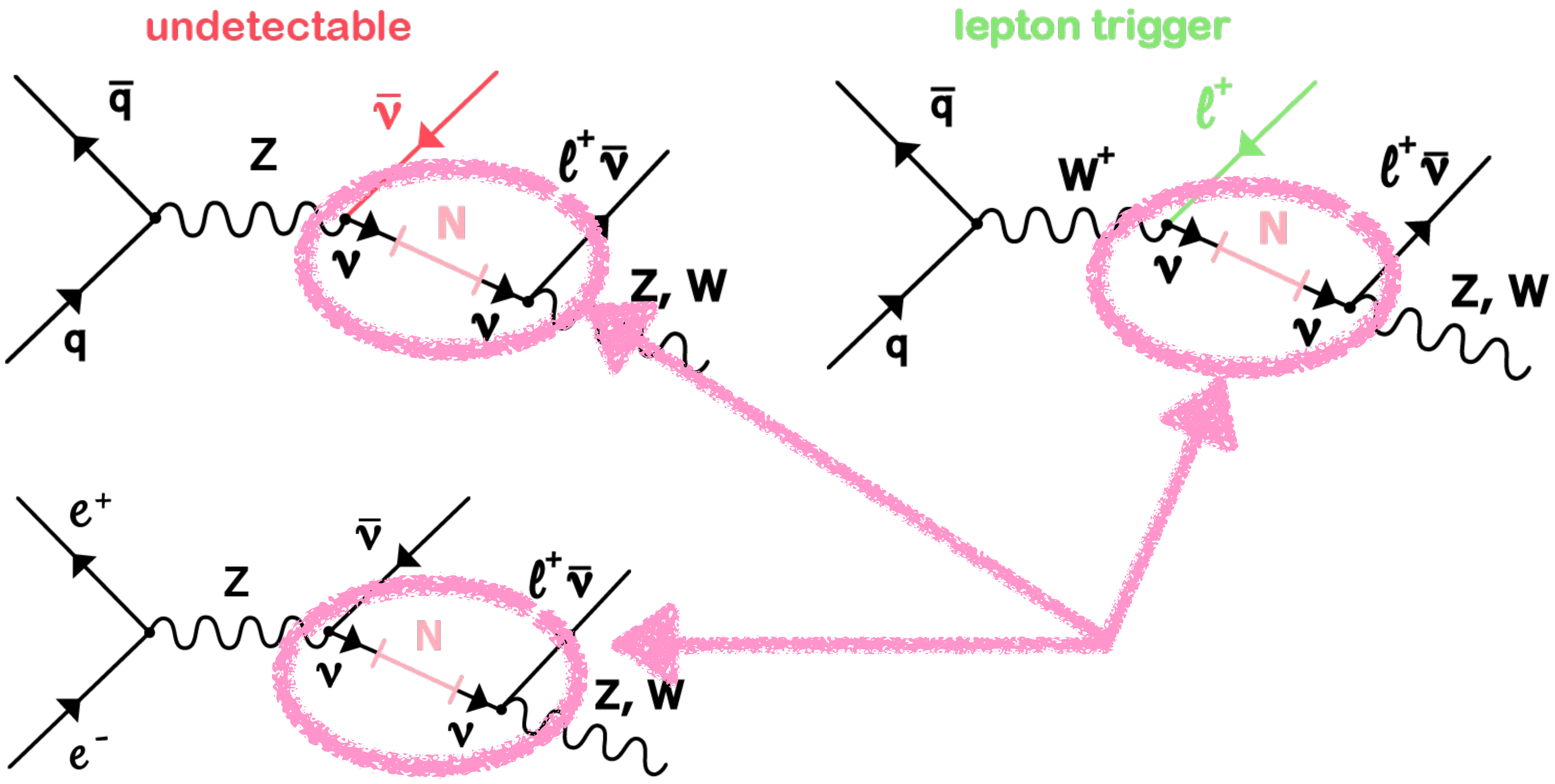
LHC
(Hadron colliders)
Trigger critical

Future lepton collider at Z pole
(FCC-ee)
Much cleaner environment



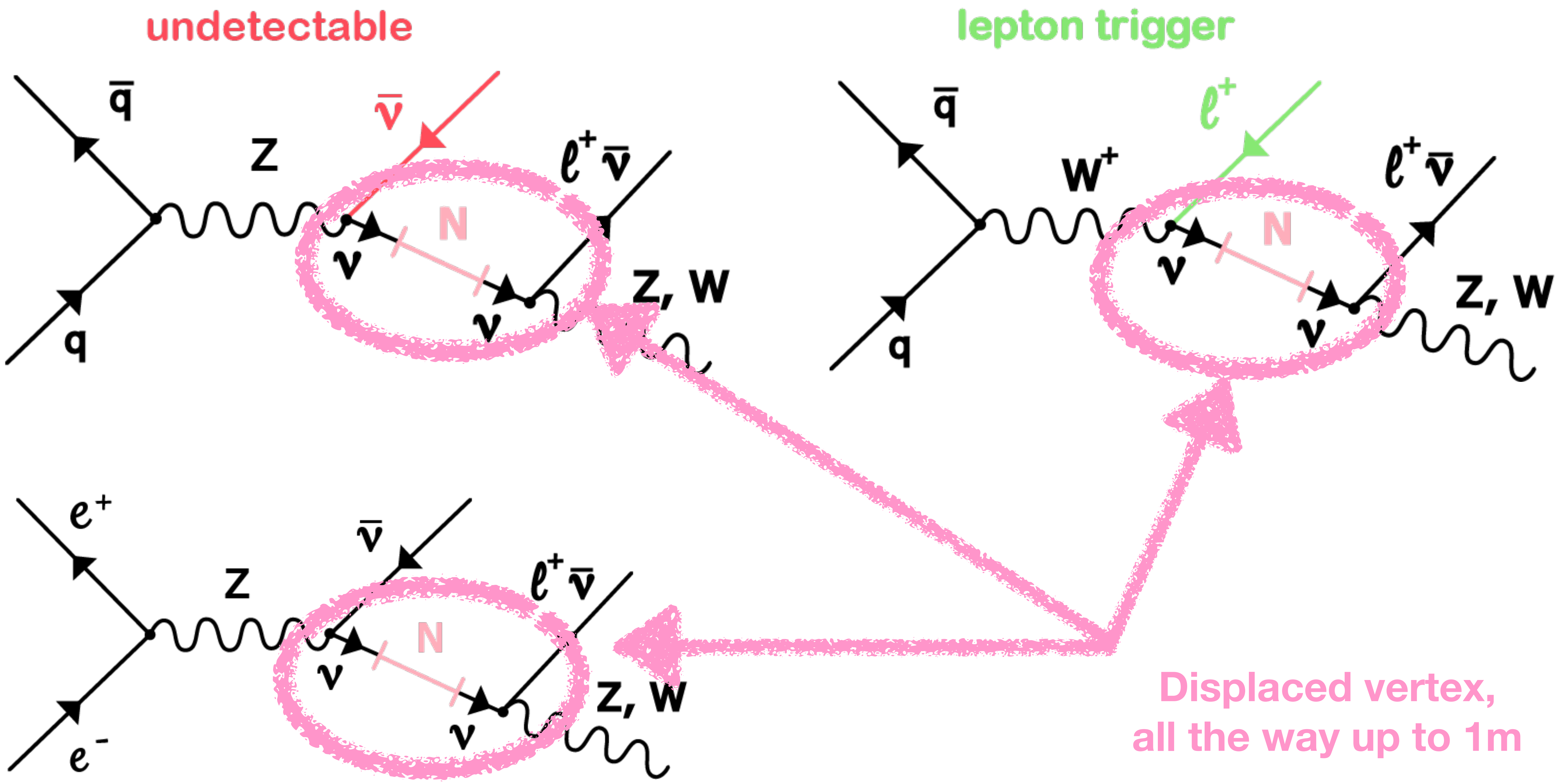
LHC
(Hadron colliders)
Trigger critical

Future lepton collider at Z pole
(FCC-ee)
Much cleaner environment



LHC
(Hadron colliders)
Trigger critical

Future lepton collider at Z pole
(FCC-ee)
Much cleaner environment



Beyond observation

- **With enough luminosity (possible at the Tera-Z run) it would be possible to distinguish between Majorana or Dirac fermions**
  - A majorana mass term will bring up different results in two observables ($Z \to \nu N$, $N \to l\ W$ channel) connected to two case-studies:
    - **lepton forward-backward charge asymmetry:** Important to distinguish the leading lepton charge (may be complicated if there is large displacement beyond the tracker)
    - **polarization measurement:** using the leading lepton momentum distributions, independently of the charge
      - arXiv:2105.06576
- For HNL with long enough lifetime → **neutrino oscillations** can be studied
  - arXiv:1709.03797

M. Drewes (Dec. 2020)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Z-Boson Decays into Majorana or Dirac (Heavy) Neutrinos

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arXiv:2105.06576v2 [hep-ph] 31 May 2021

We computed the kinematics of Z-boson decay into a heavy–light neutrino pair when the Z-boson is produced at rest in e^+e^- collisions, including the subsequent decay of the heavy neutrino into a visible final state containing a charged-lepton. We concentrated on heavy-neutrino masses of order dozens of GeV and the issue of addressing the nature of the neutrinos – Dirac fermions or Majorana fermions. We find that while it is not possible to tell the nature of the heavy and light neutrinos on an event-by-event basis, the nature of the neutrinos can nonetheless be inferred given a large-enough sample of heavy–light neutrino pairs. We identify two observables sensitive to the nature of neutrinos. One is the forward-backward asymmetry of the daughter-charged-leptons. This asymmetry is exactly zero if the neutrinos are Majorana fermions and is non-zero (and opposite) for positively- and negatively-charged daughter-leptons if the neutrinos are Dirac fermions. The other observable is the polarization of the heavy neutrino, imprinted in the laboratory-frame energy distribution of the daughter-charged-leptons. Dirac neutrinos and antineutrinos produced in e^+e^- collisions at the Z-pole are strongly polarized while Majorana neutrinos are at most as polarized as the Z-bosons.

I. INTRODUCTION

Spin one-half massive fermions in four spacetime dimensions can be classified into two types: Majorana fermions and Dirac fermions. Majorana fermions are self-conjugate; they are their own antiparticles. Dirac fermions are not. A massive Dirac field describes four independent degrees of freedom, a massive Majorana field describes two independent degrees of freedom. Dirac fields are complex and can transform under complex representations of symmetry groups (gauged or global). Majorana fields are, in some sense, real and can only transform under real representations of unbroken symmetries (gauged or global).

All known fundamental fermions are massive, except, at most, the lightest of the three neutrinos. With the exception of the neutrinos, all have nonzero electric charge. Hence, the charged leptons (e, μ, τ) and all quarks are Dirac fermions. Experimental data to date are agnostic concerning the nature of the neutrinos – Majorana or Dirac fermions.

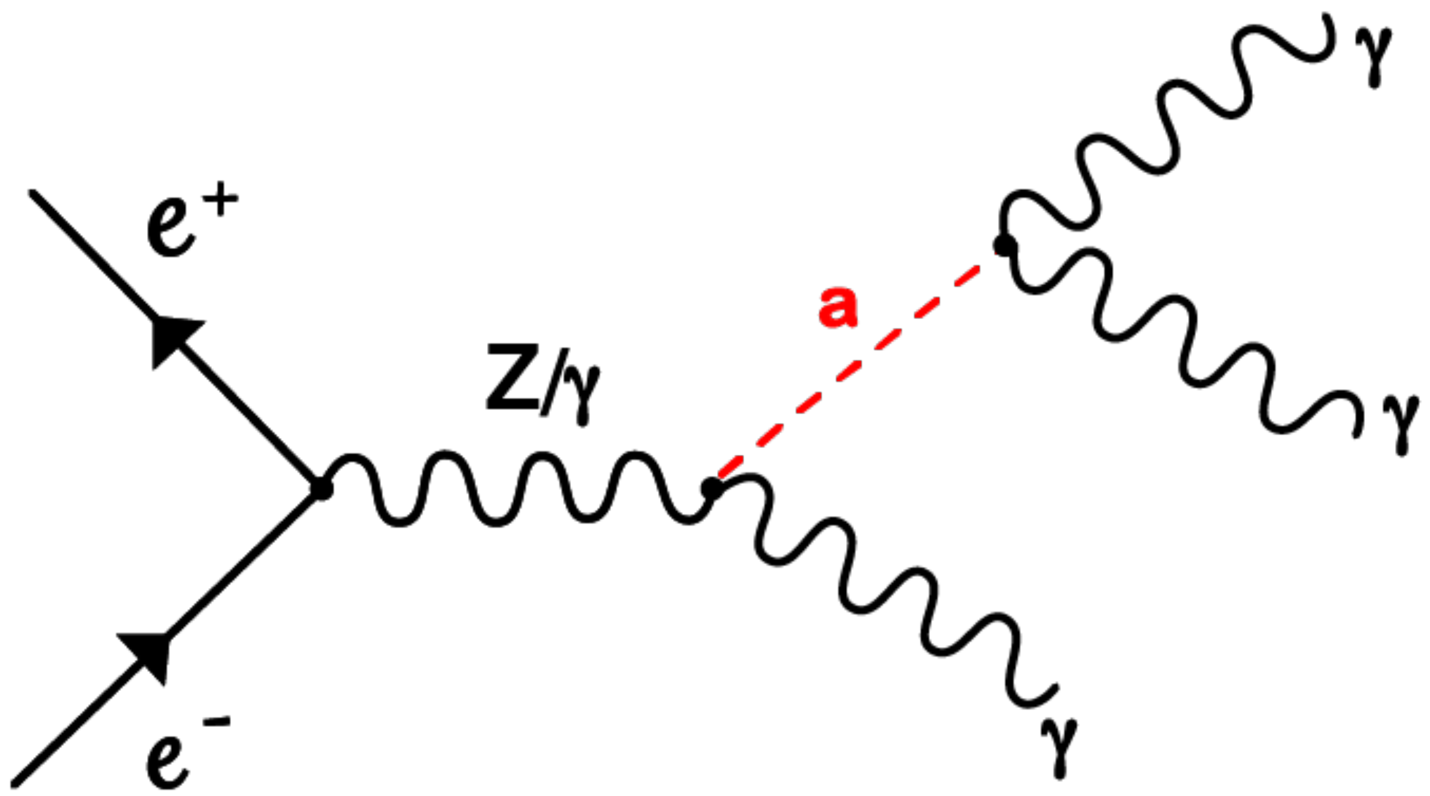
The traditional way to probe the nature of neutrinos is to test the conservation of lepton number (see, for example, [1, 2]). Majorana neutrinos, since they are self-conjugate, cannot be charged under the lepton-number symmetry, rendering it, necessarily, an approximate symmetry. Evidence for the violation of lepton-number symmetry (by two units) would translate, almost necessarily, into proof that neutrinos are Majorana fermions [3–5] (see also [6] for a modern discussion). The most powerful probes of lepton-number violation are low-energy particle and nuclear physics processes, including searches for neutrinoless double-beta decay, $(\mu^- \to e^+)$-conversion in nuclei, and forbidden meson decays (e.g. $K^+ \to \pi^-\mu^+\mu^+$). No unambiguous experimental evidence for lepton-number violation has been found yet [7].

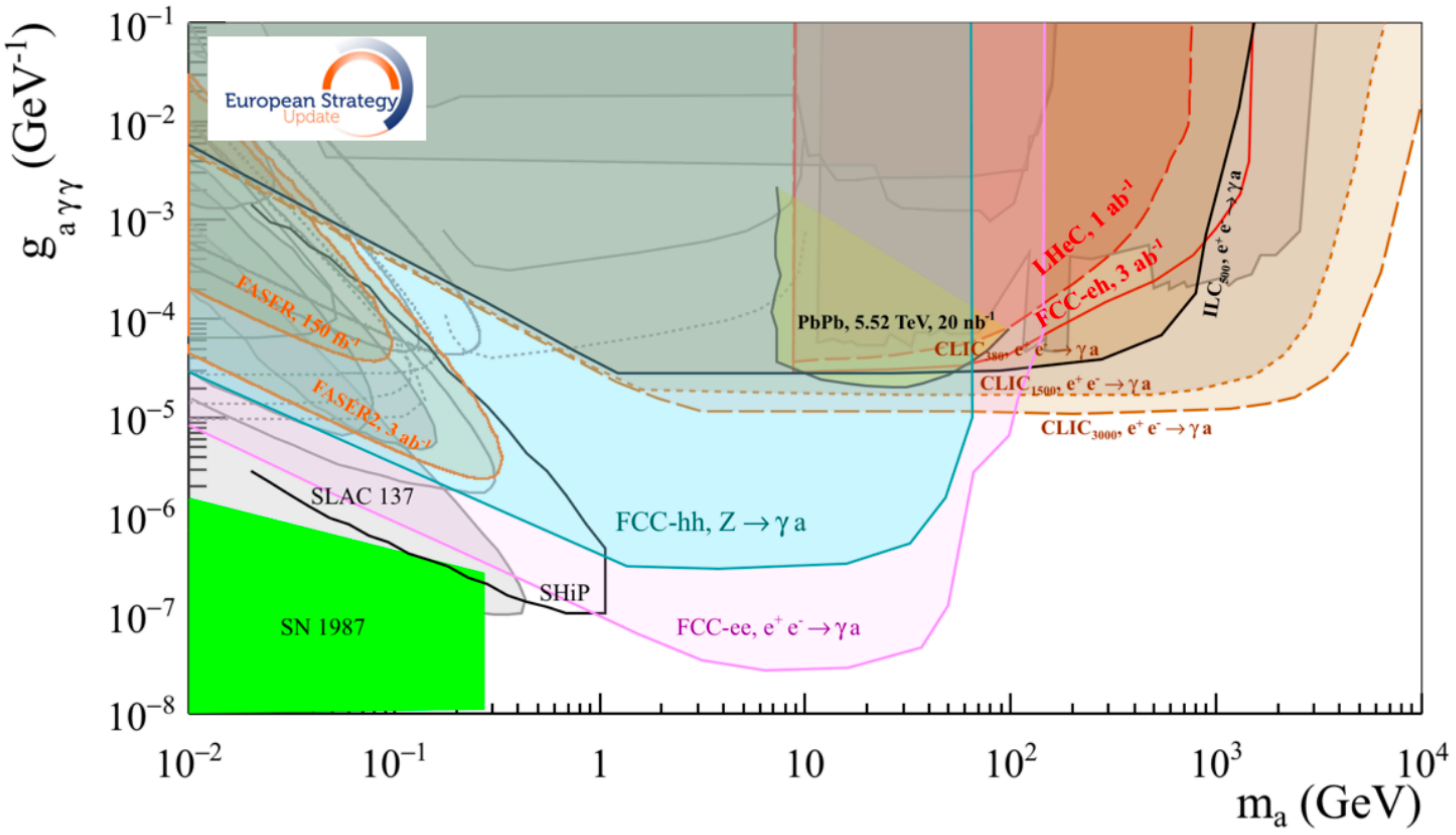
The physics behind nonzero neutrino masses remains unknown. One can, however, affirm that nonzero neutrino masses imply the existence of new particles (for an overview see, for example, [8]). The properties – spin, mass, charge – of these new particles is currently unknown and the subject of extensive theoretical and experimental particle physics research. Information on the nature of neutrinos is expected to illuminate the origin of neutrino masses in a very fundamental way.

New neutral fermions are common side effects of the mechanism responsible for nonzero neutrino masses. The popular Type-I seesaw mechanism [9–14], for example, posits the existence of at least two gauge-singlet fermion fields in addition to the known matter fields of the Standard Model. These are allowed nonzero Majorana-mass terms and couple to the active neutrinos ν_e, ν_μ, ν_τ via Yukawa interactions. After electroweak symmetry breaking, all neutral fermions – linear combinations of the active neutrinos and the new degrees of freedom – acquire masses, all are Majorana fermions, and all couple with different strength to the electroweak gauge bosons and the Higgs boson. In the traditional Type-I seesaw, the neutral fermions "split" into three mostly-active neutrinos that are very light and at least two much heavier states that are predominantly composed of gauge-singlet fermions. We refer to the former as light neutrinos and the latter as heavy neutrinos. In this scenario, the couplings of the heavy neutrinos are related

Long-lived ALPs

- Commonly produced with a photon or a Z decaying into photons
- For small couplings and light ALPs, the ALP decay vertex can be considerably displaced from the production vertex → LLP





Exclusion limits for ALPs coupled to photons. All curves correspond to 90% CLexclusion limits, except for LHeC/FCC-eh (95% CL exclusion limits), FCC-ee (observation offour signal events) and FCC-hh (observation of 100 signal events). From the Briefing Book

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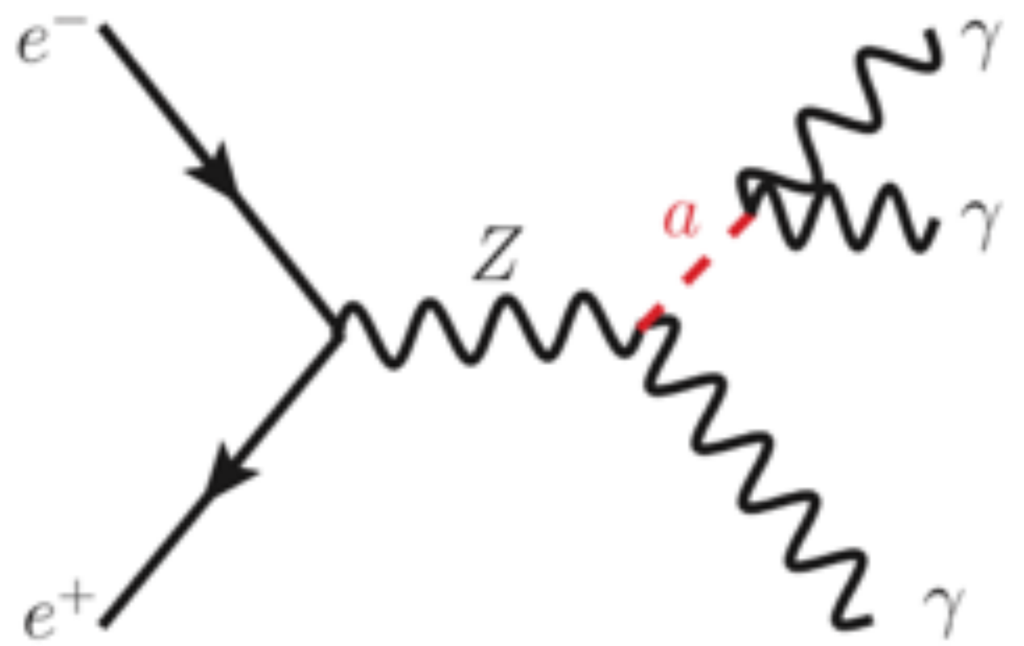
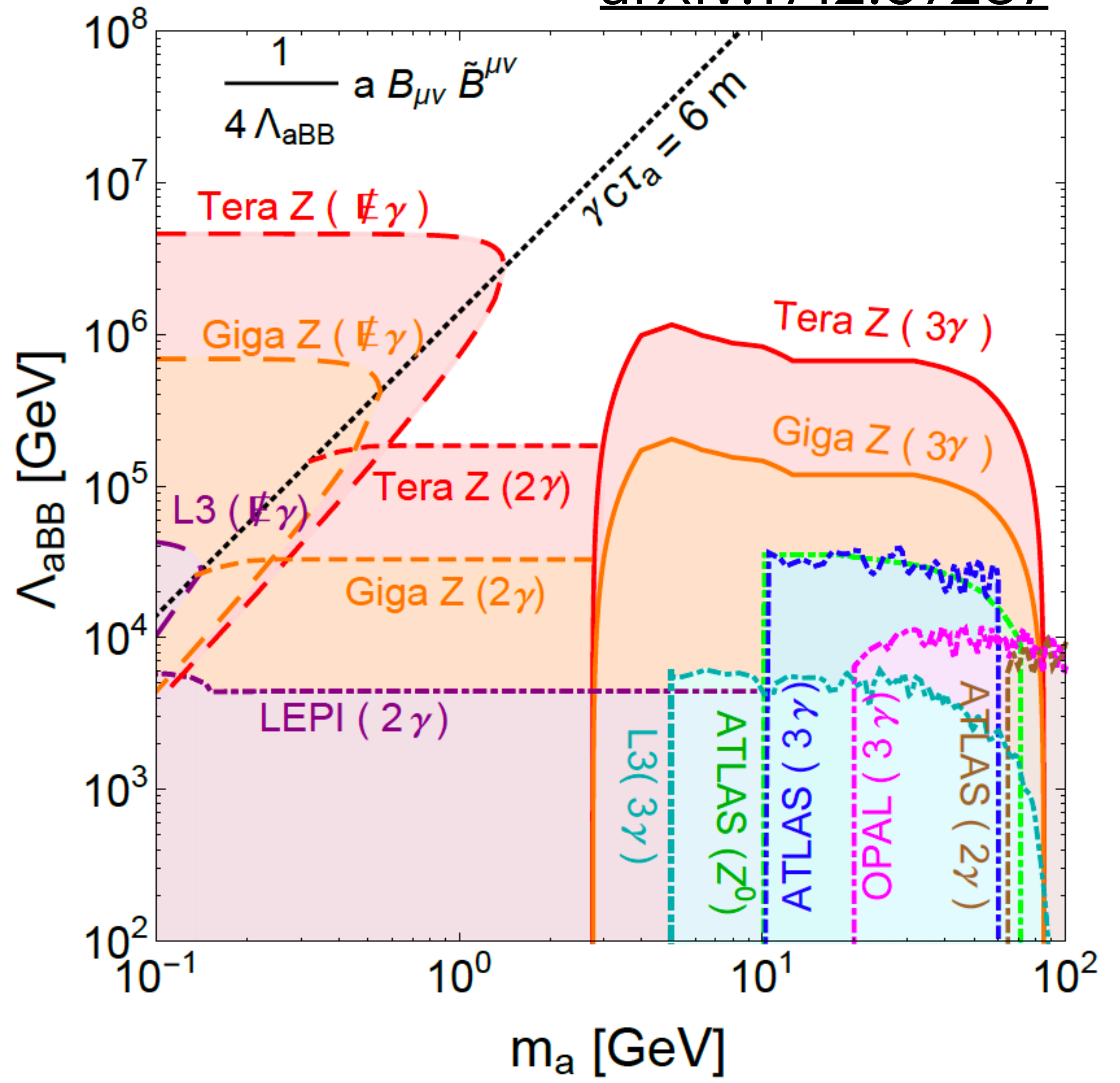
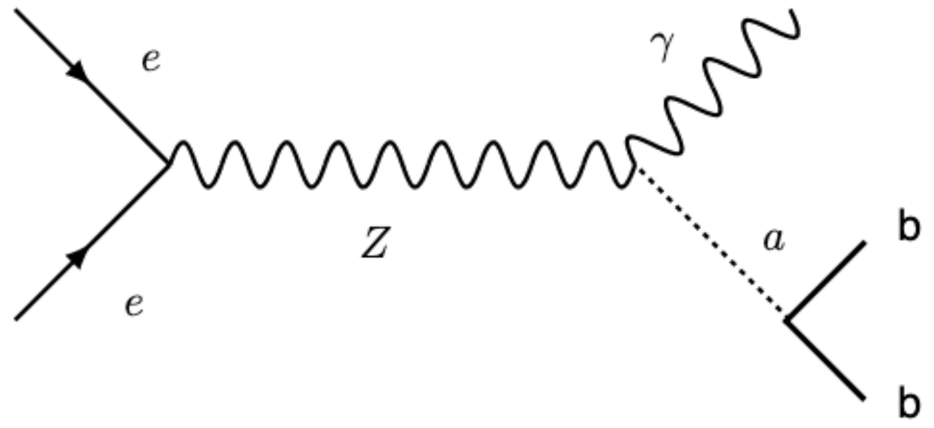
FCC-ee: ALPs

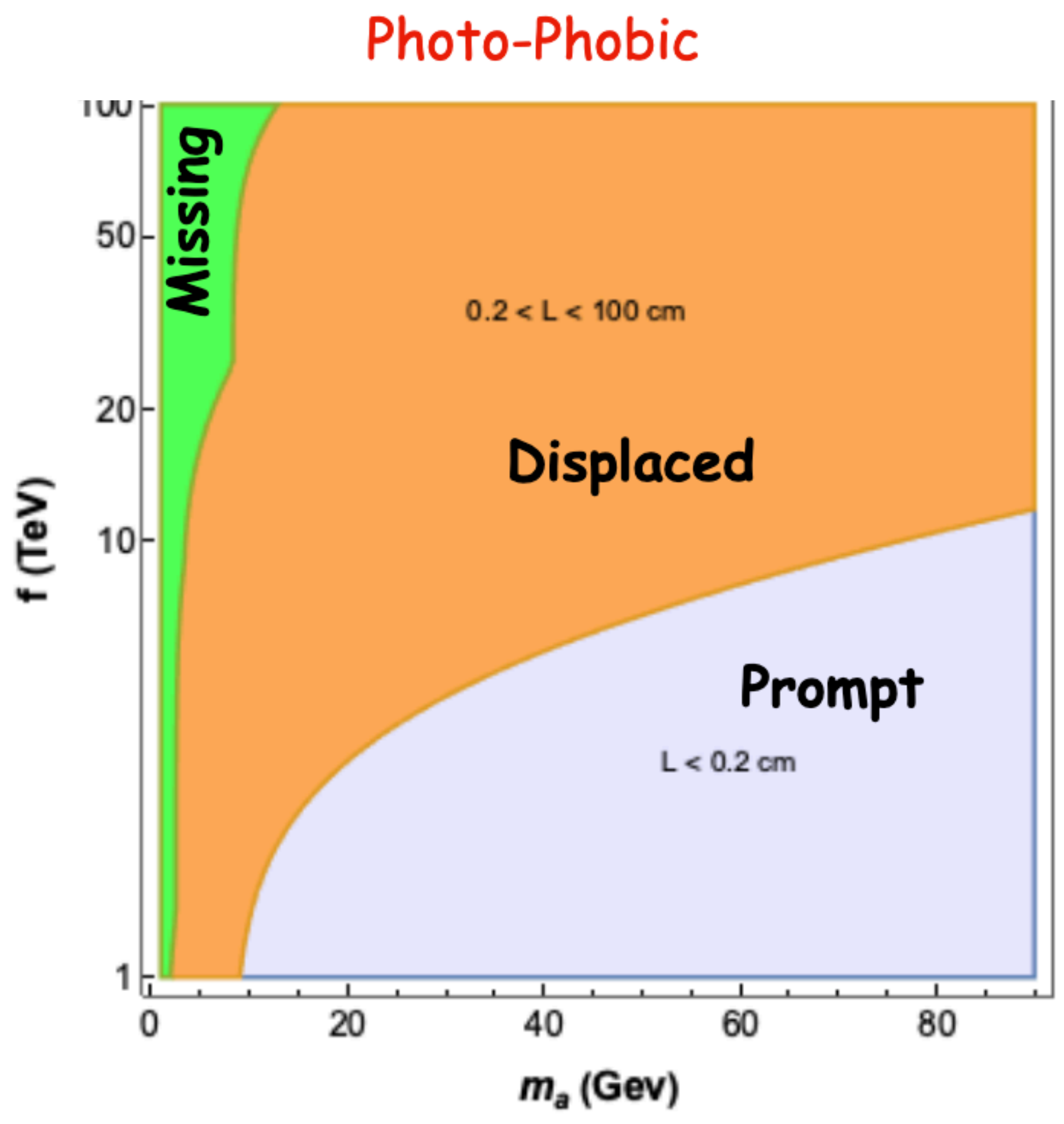
- Specially sensitive final states at the FCC-ee :
  - γ + MET for very light a
  - $\gamma\,\gamma$ for light a
  - $\gamma\,\gamma\,\gamma$ for heavier a
  - Orders of magnitude of parameter space accessible
- Recent paper A. Iyer (June 2021)
  - light (composite) axion-like particles
  - arXiv:2104.11064

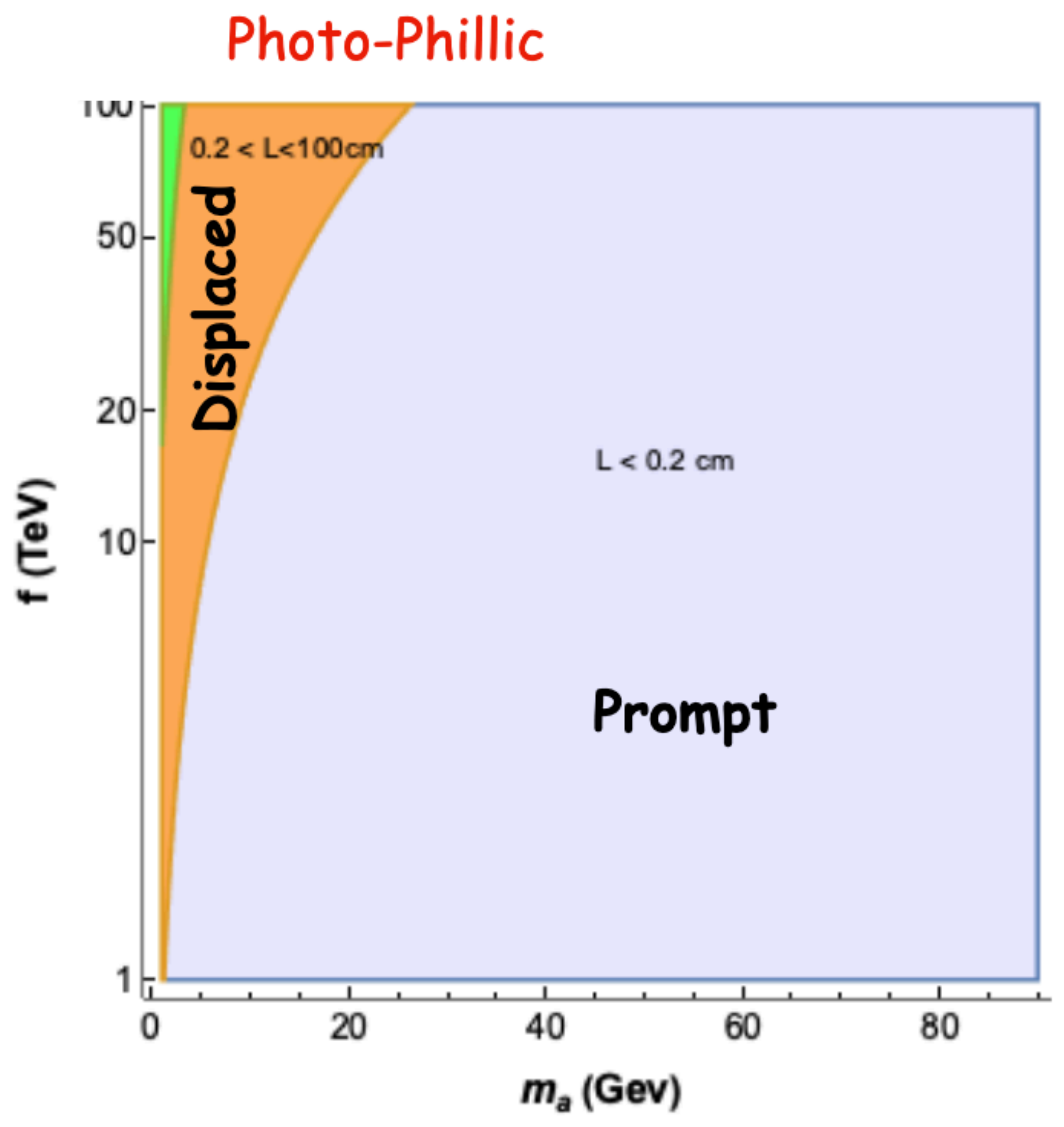


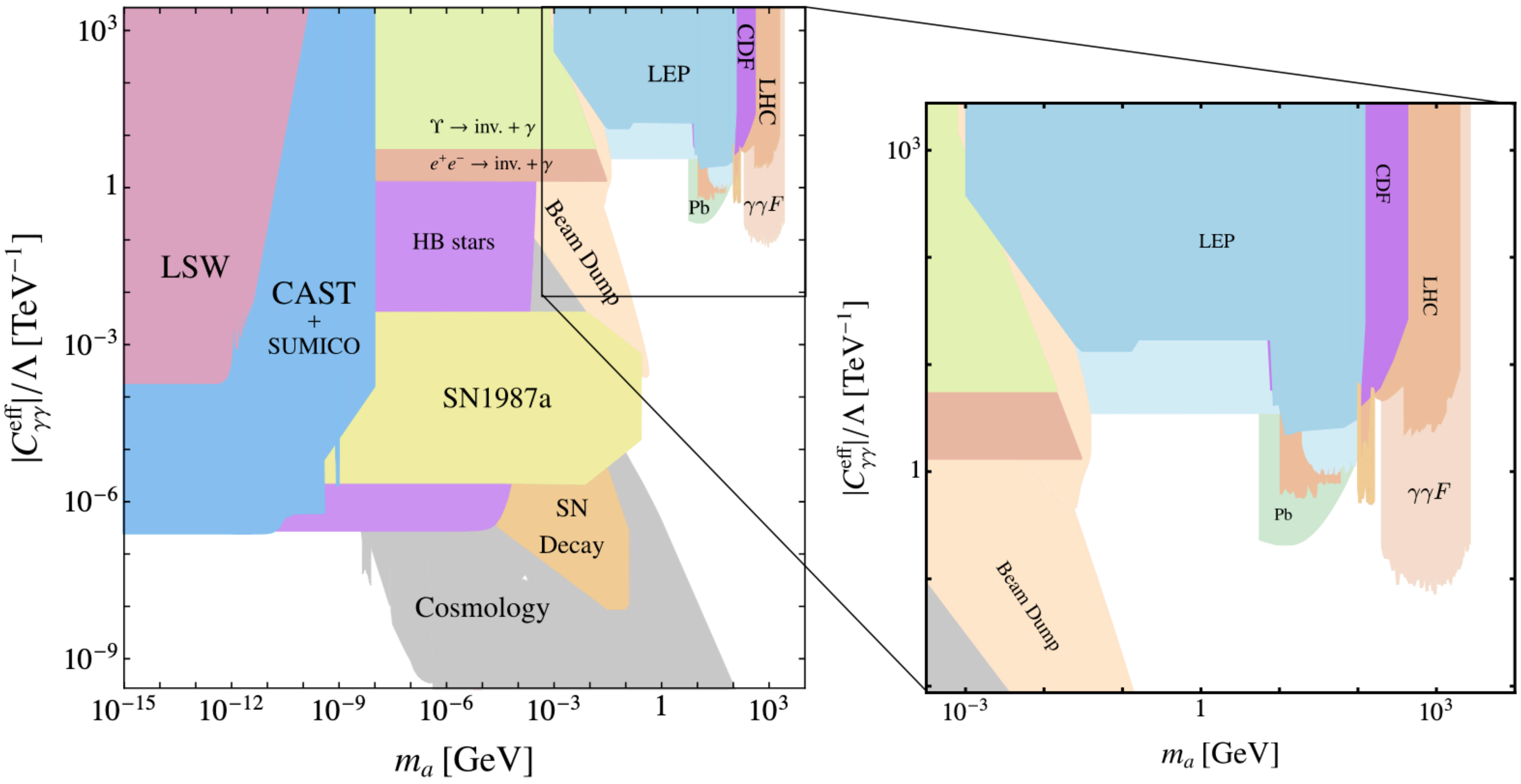
arXiv:1712.07237











Summary plot of constraints on the parameter space spanned by the ALP mass and ALP-photon coupling with enlarged display of the constraints from collider searches from arXiv:1808.10323

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More LLPs at FCC-ee

- Finding valid motivations for LLP at the FCC is certainly not a problem
  - Higgs portal, dark glueball (arXiv:1911.08721)
  - Neutral naturalness (arXiv:1506.06141)
  - Folded SUSY (arXiv:1911.08721)

FCC-ee

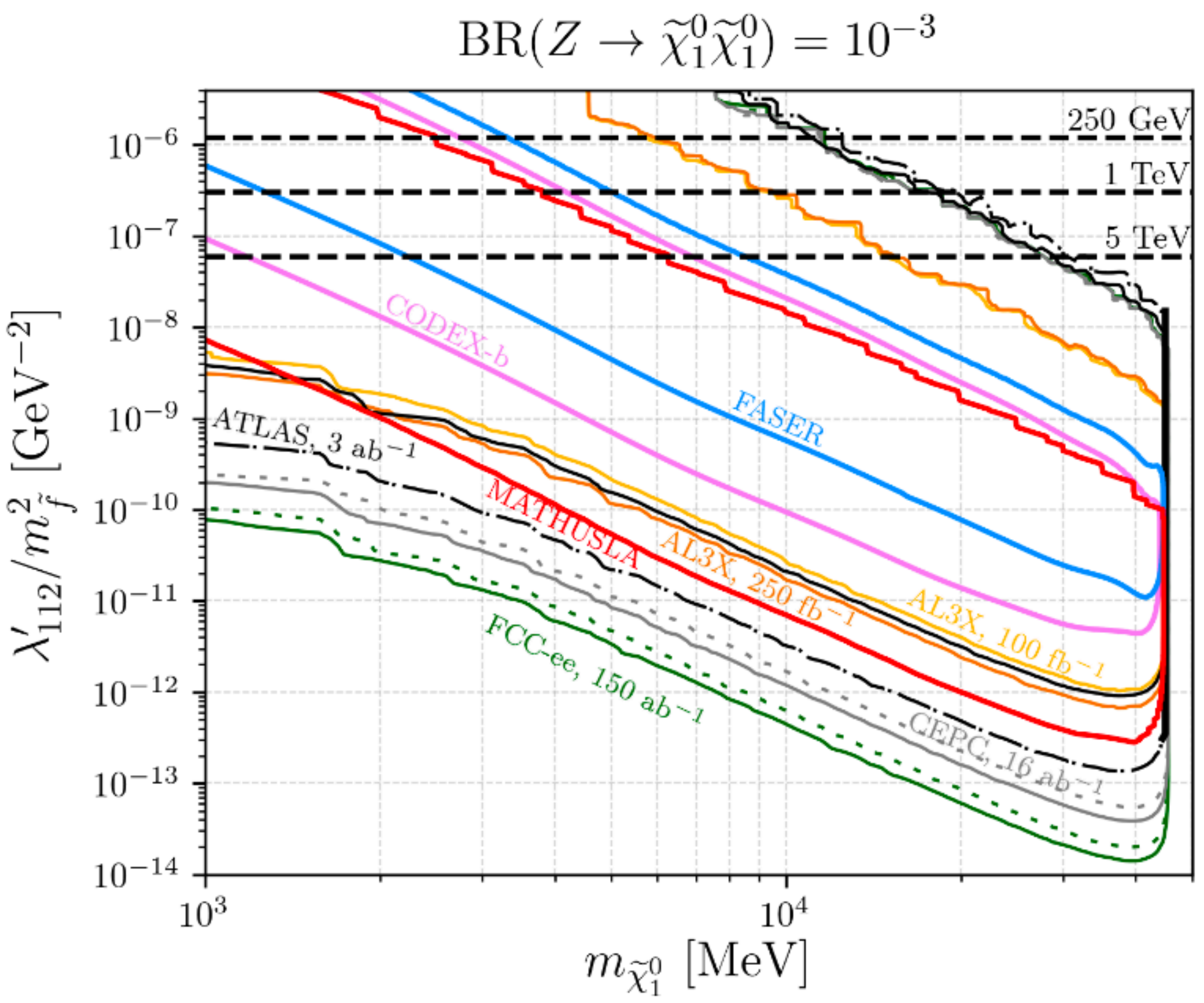
  - Neutralinos (arXiv:1904.10661)
  - Dark photon (arXiv:1909.02312)

FCC-he

  - Wino and higgsino dark matter with a disappea

FCC-hh

C (2019) 79:469)



arXiv:1904.10661

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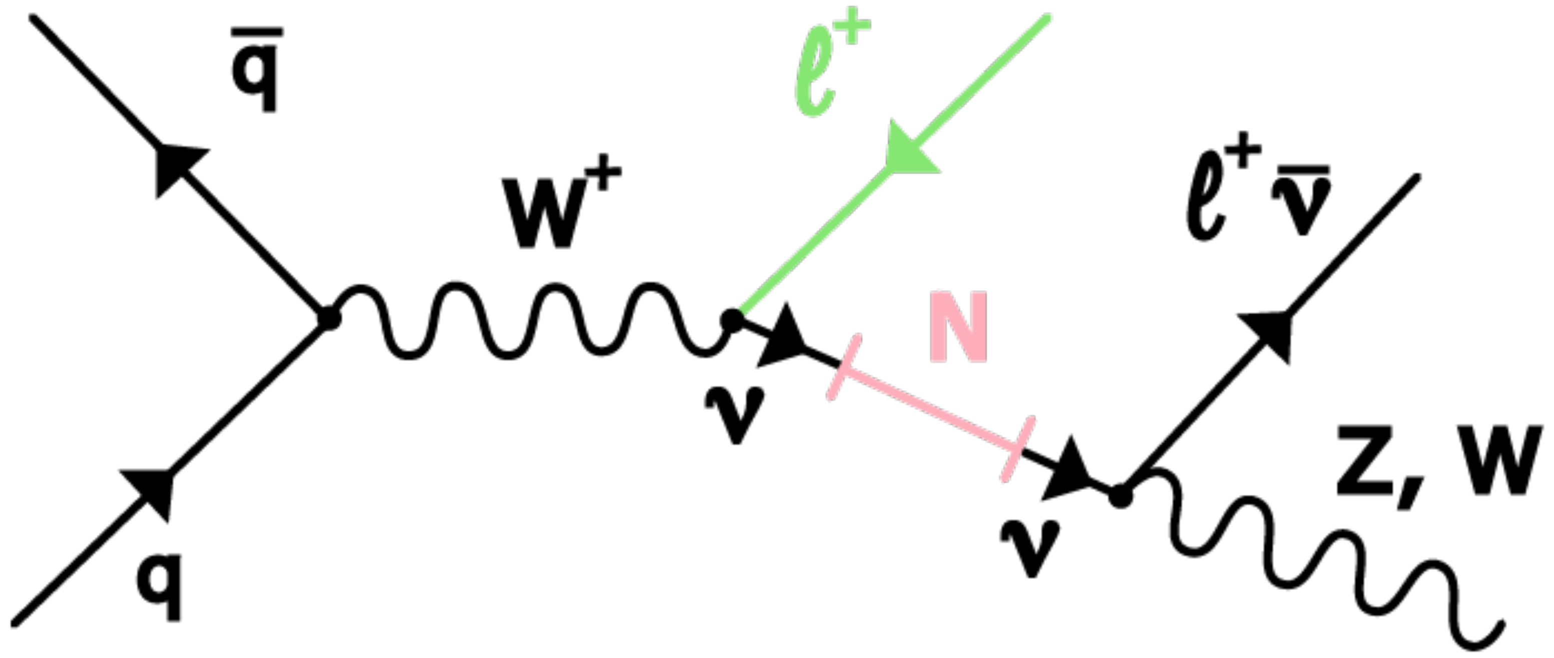
LLP subgroup

- FCC has a subgroup dedicated to LLP searches, under the BSM physics group (https://indico.cern.ch/category/5664/), subscribe to the mailing list (FCC-PED-PhysicsGroup-BSM@cern.ch) to participate
- Simulations under way with Madgraph5 v3.2.0 + Pythia8 + Delphes
- Many master theses and projects: Sissel Bay Nielsen (HNL), Rohini Sengupta (HNL), Lovisa Rygaard (HNLs) + (ALPs), Tanishq Sharma (HNL), Magdalena Vande Voorde (Exotic Higgs), Dimitri Moulin (HNL)
- Lot of work done for snowmass, stay tuned for the upcoming FCC week:
    - https://arxiv.org/abs/2203.06520
    - https://arxiv.org/abs/2203.05502
    - https://arxiv.org/abs/2209.13128

FCC-hh

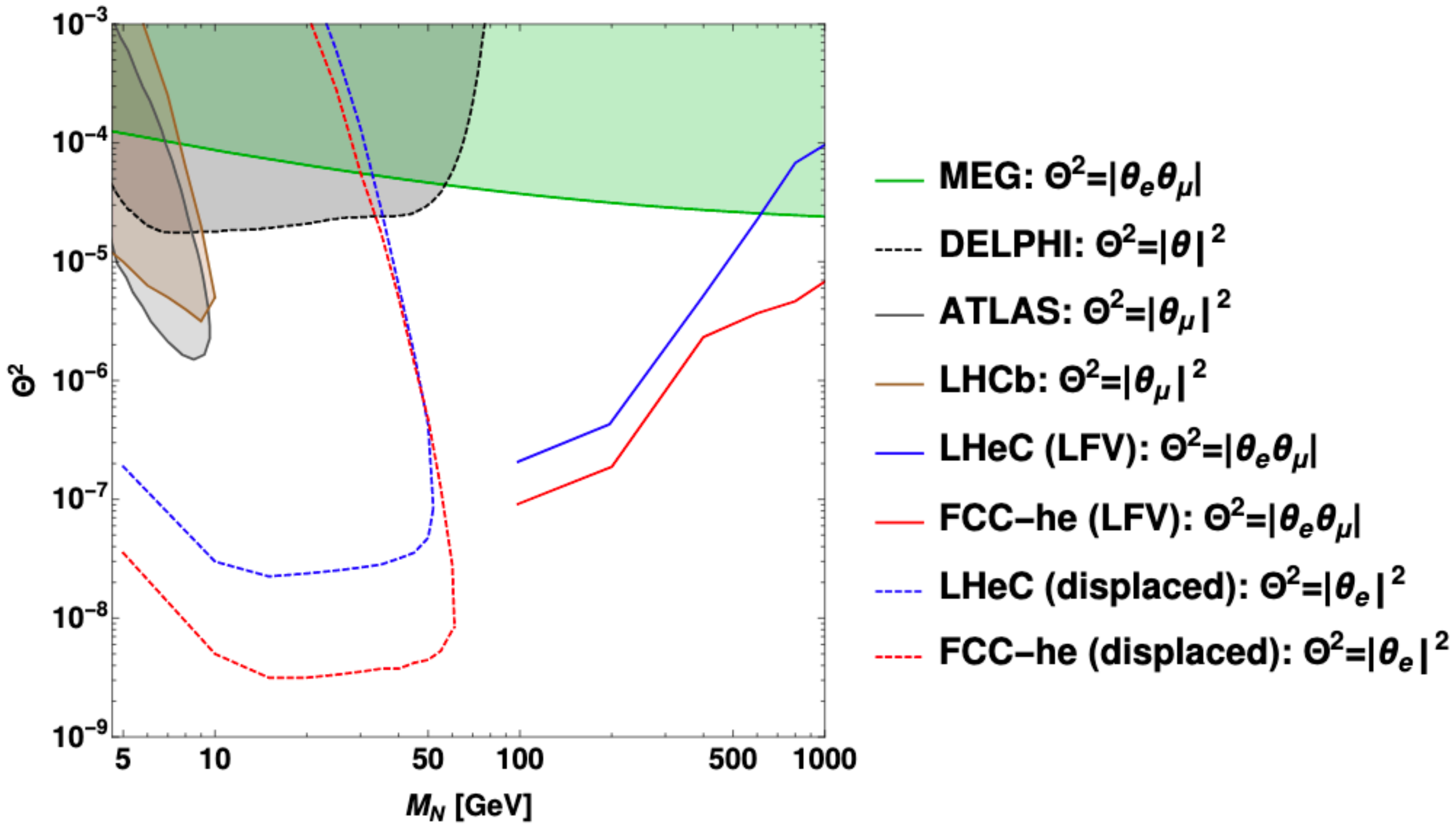


- The high luminosity and large centre of mass energy at the FCC-hh will help probe additional parameter space
  - High mass, but mixing angles of interest to neutrino mass models not accesible
- At the 100 TeV pp, 10^{13} W bosons → HNL produced in W decays
  - Discovery signatures: three leptons, displaced vertex
  - More complex environment than FCC-ee: pile-up/backgrounds/lifetime/trigger
- **Allows for both in flavour and charge characterisation of the produced neutrino**
  - Study of flavour-sensitive mixing angles
  - Test of the fermion violating nature of the intermediate (Majorana) particle.
- If we find hints for HNL at FCC-ee, the FCC-hh will help understanding more about them

FCC-eh

- The FCC-eh will also extend the mass reach of the FCC-hh for HNL
- The FCC-eh will offer additional sensitivity for LFV
  - Also in displaced signatures (long-lived)

arXiv:1908.02852

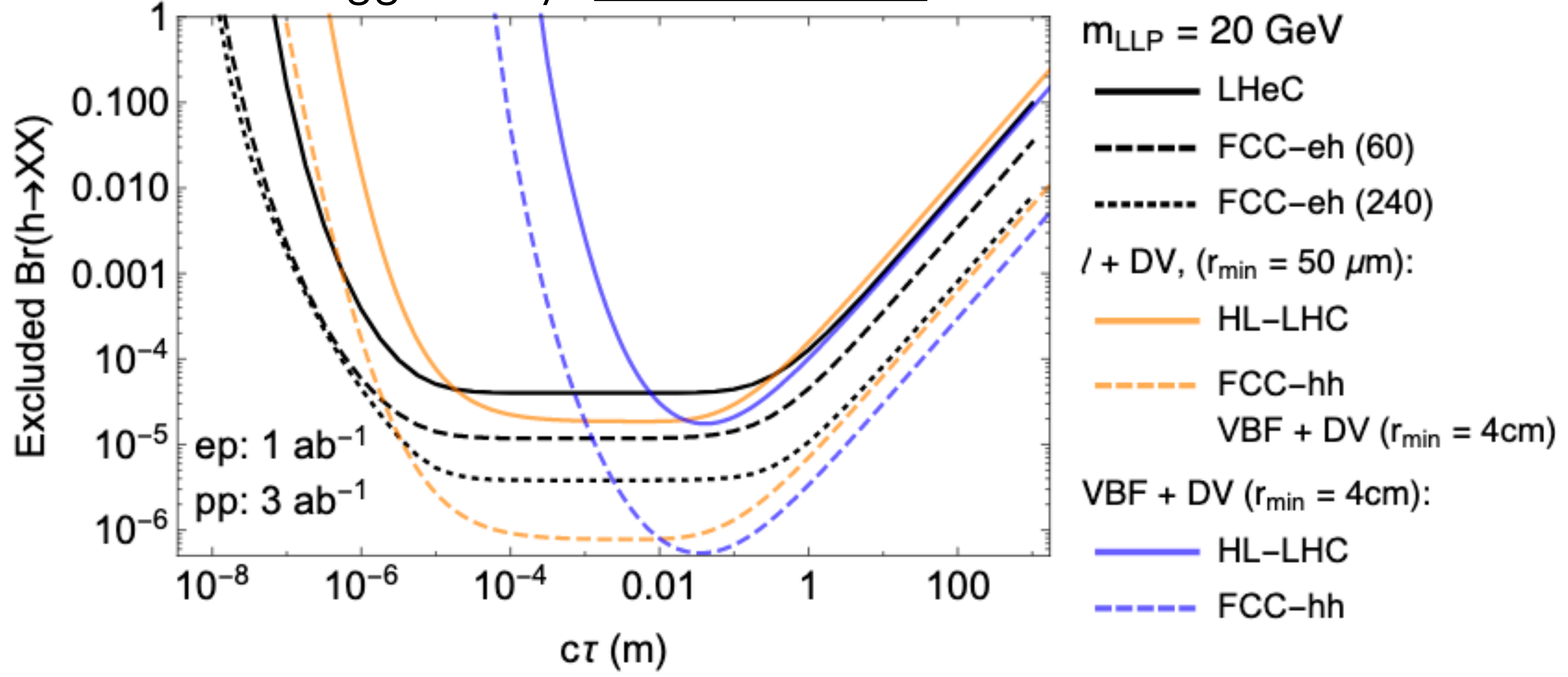


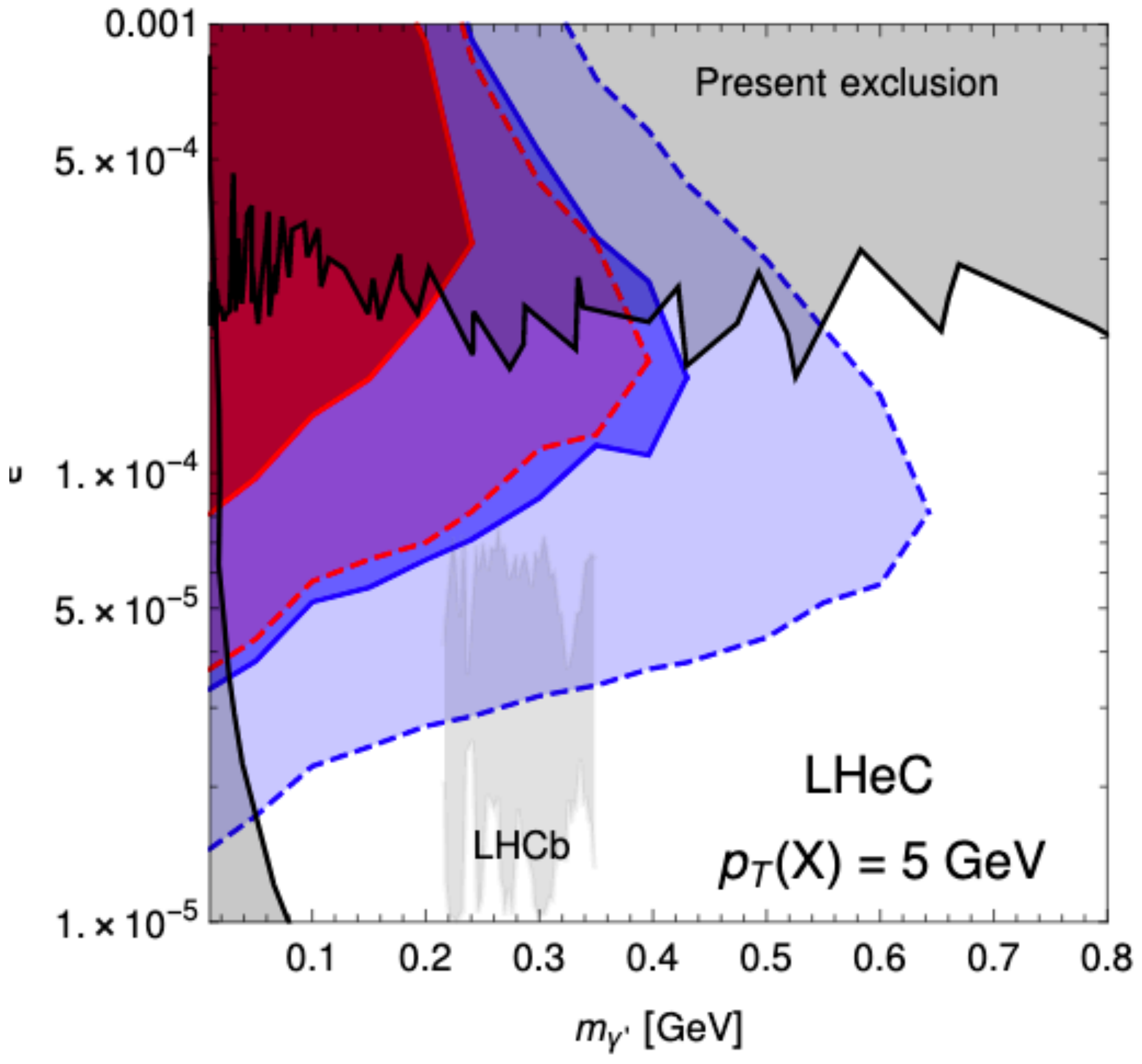
Ref: Ryu Sawada
RGS FCC workshop

Future Hadron colliders

- Options on the table (ep, pp)
  - LHeC@CERN
  - HE-LHC@CERN [27 TeV]
  - FCC-eh/hh@CERN [3.5/100 TeV]
  - SppC@China [75-150 TeV]

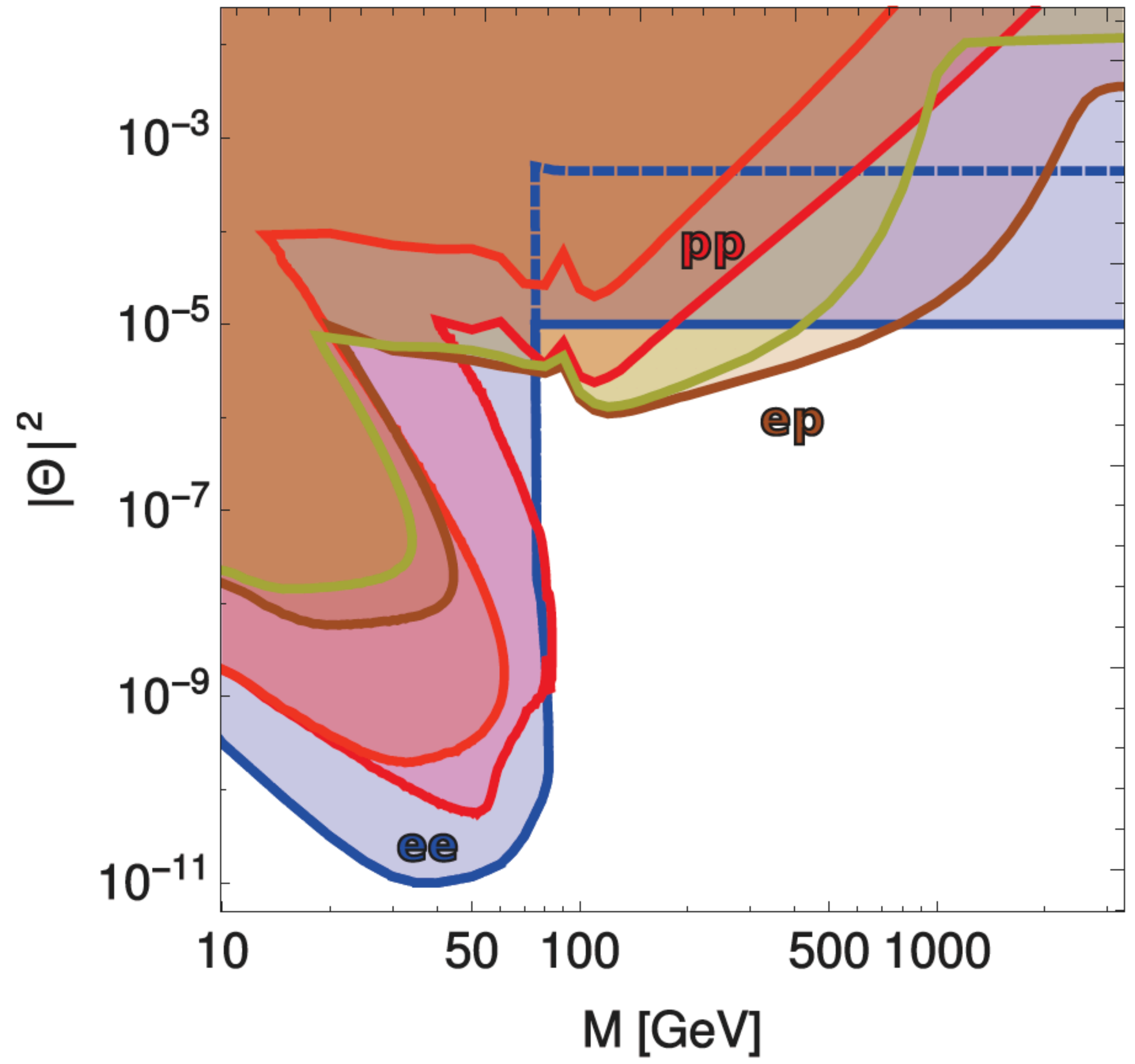
LLP in Higgs decays arXiv:1712.07135





Dark photon:
arXiv:1909.02312

Eur.Phys.J C (2019) 79:469
Wino and higgsino dark matter with a disappearing track signatures
FCC-hh
...



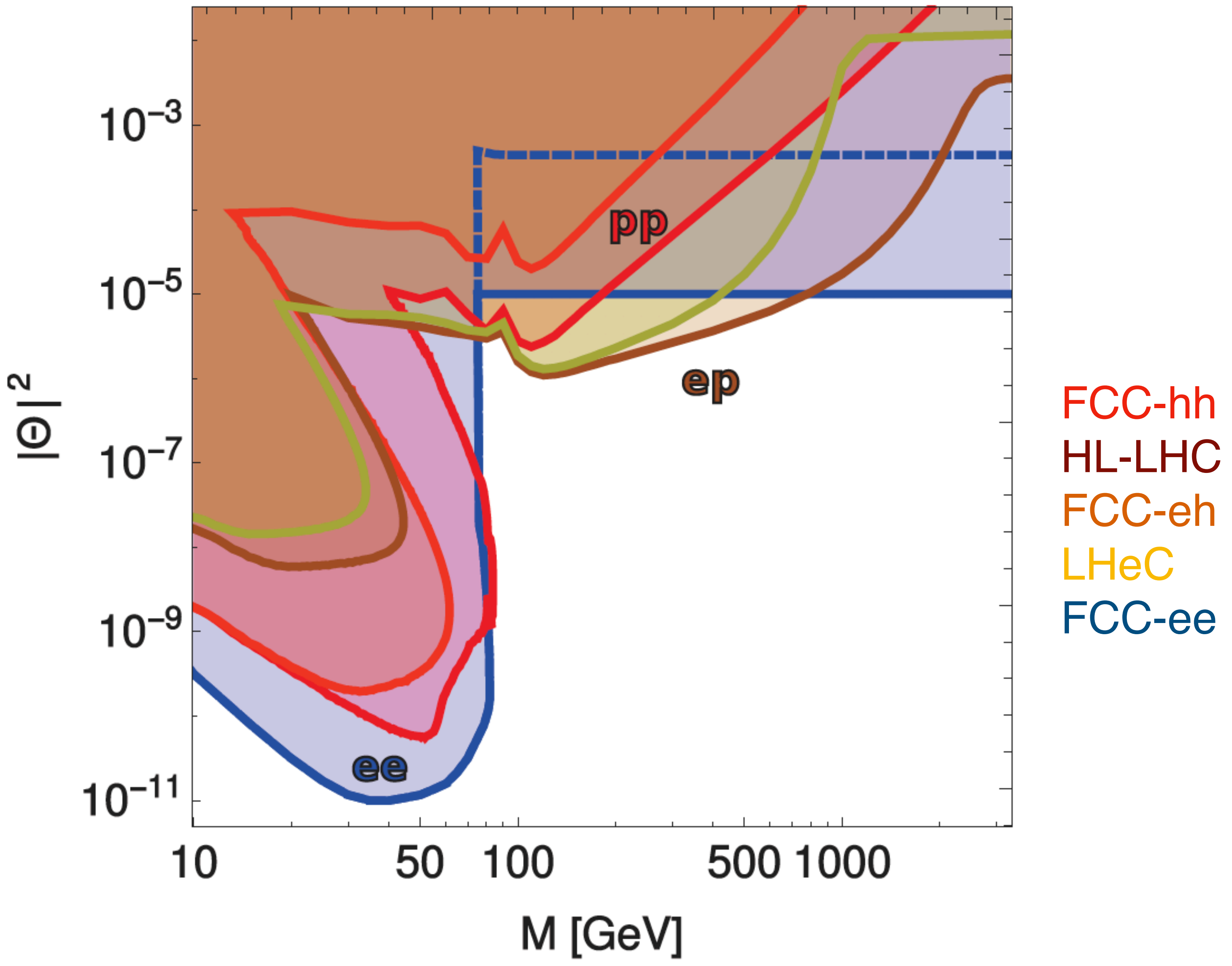
FCC-hh
HL-LHC
FCC-eh
LHeC
FCC-ee

HNL complementarity
arXiv:1612.02728

Complementarity

- The complementarity of the three different stages of the FCC provides unique potential to discover and pin down these particles

arXiv:1612.02728



FCC-ee

Indirect constrains from precision SM measurements (not discussed)

Direct search: single HNL production in Z decays

Sensitive to 10^{-11} for M below the W mass

FCC-hh

Direct search: single HNL production in W/Z decays

Lepton Number Violation, Lepton Flavor Violation

can test heavy neutrinos with masses up to ~2 TeV

FCC-eh

Can extend the reach of the FCC-hh up to ~2.7 TeV

Best reach above W mass

Sensitive to LFV and Lepton-Number-violation signatures

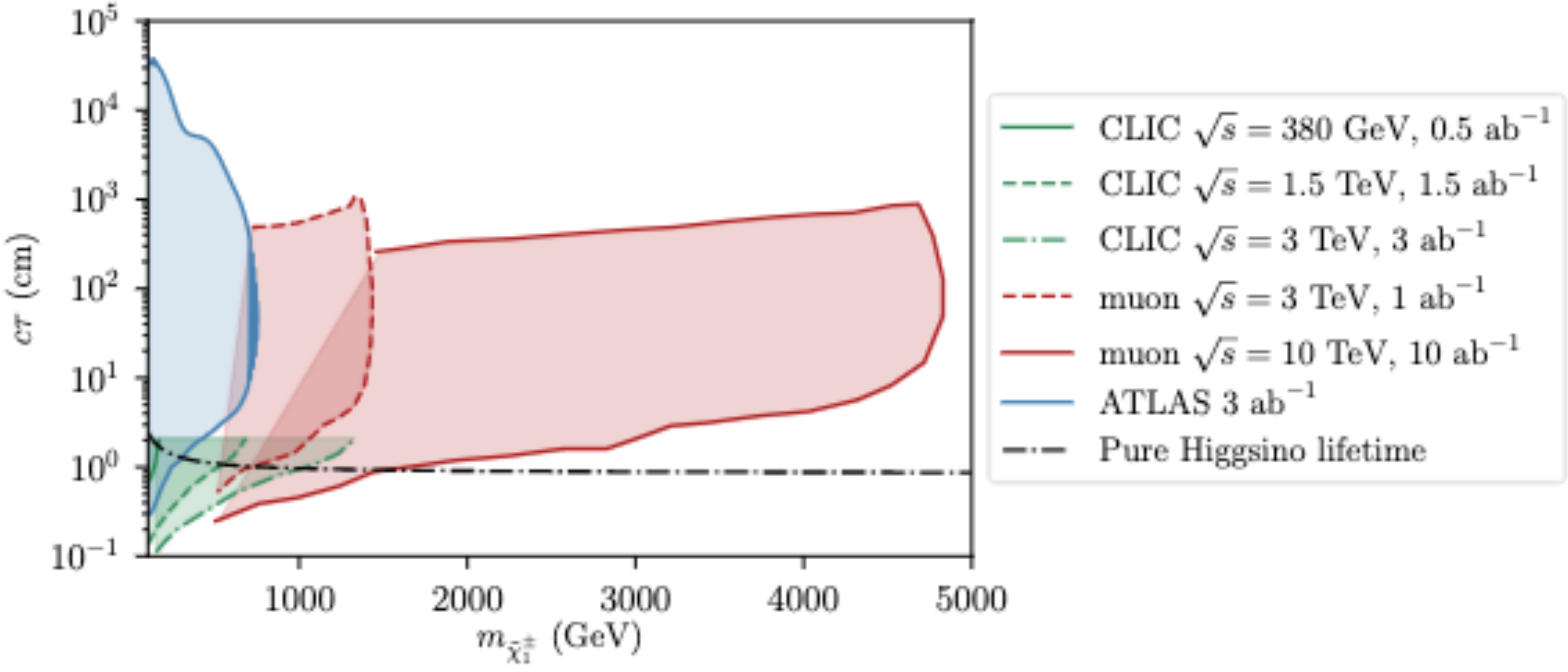
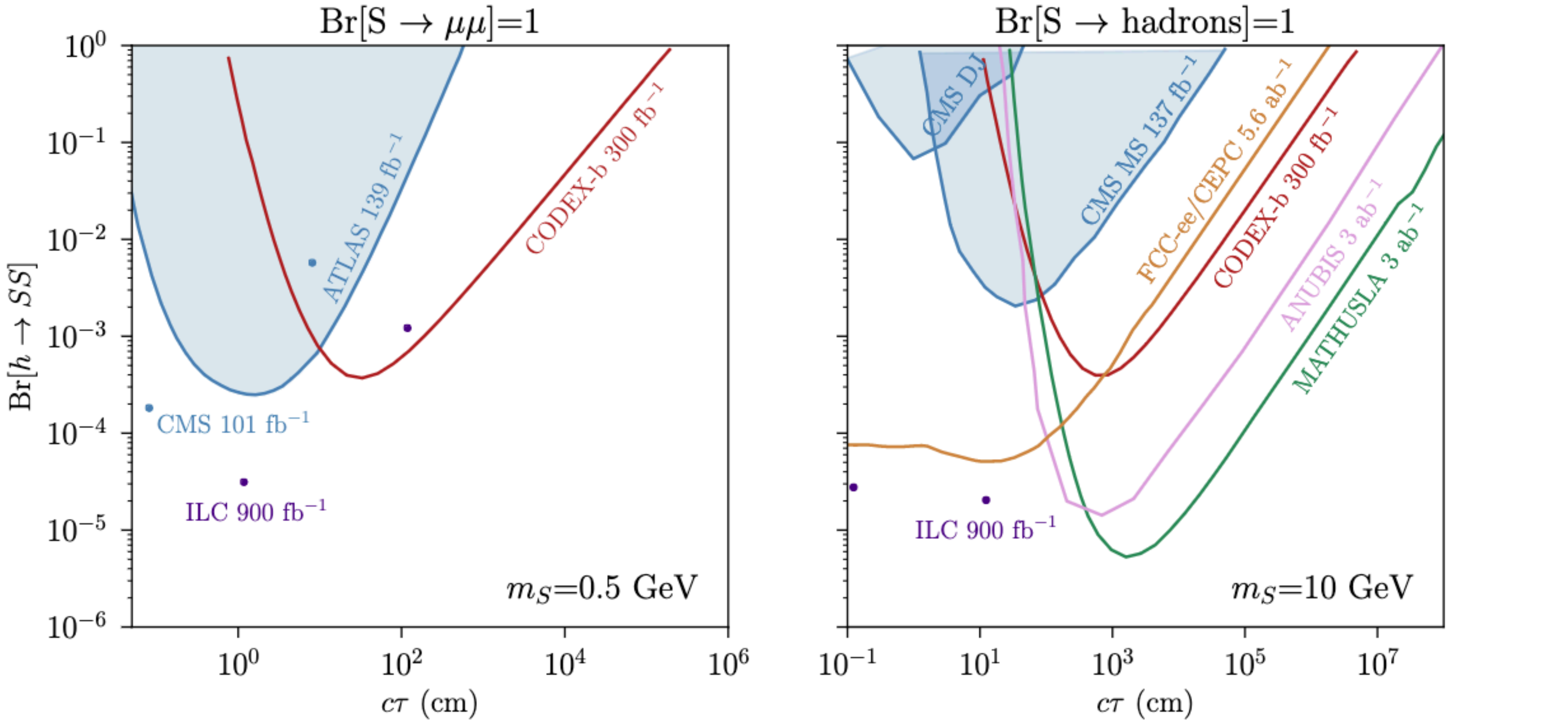
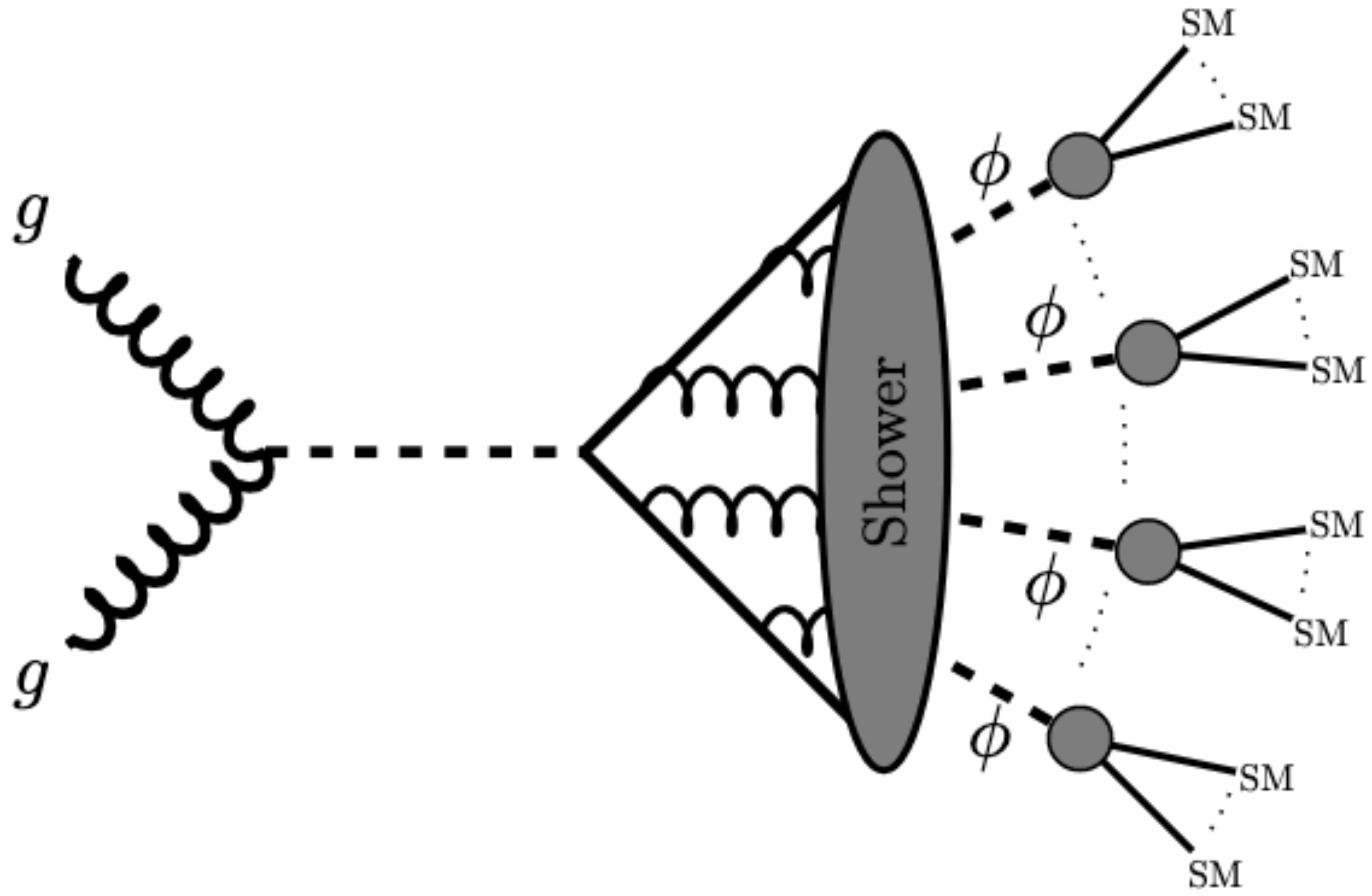


Figure 22: Projected reach of disappearing track signatures in the chargino mass–$c\tau$ plane at 95% CL exclusion from CLIC (green curves) [403], a muon collider [404], and ATLAS at the HL-LHC (blue curve) [236].

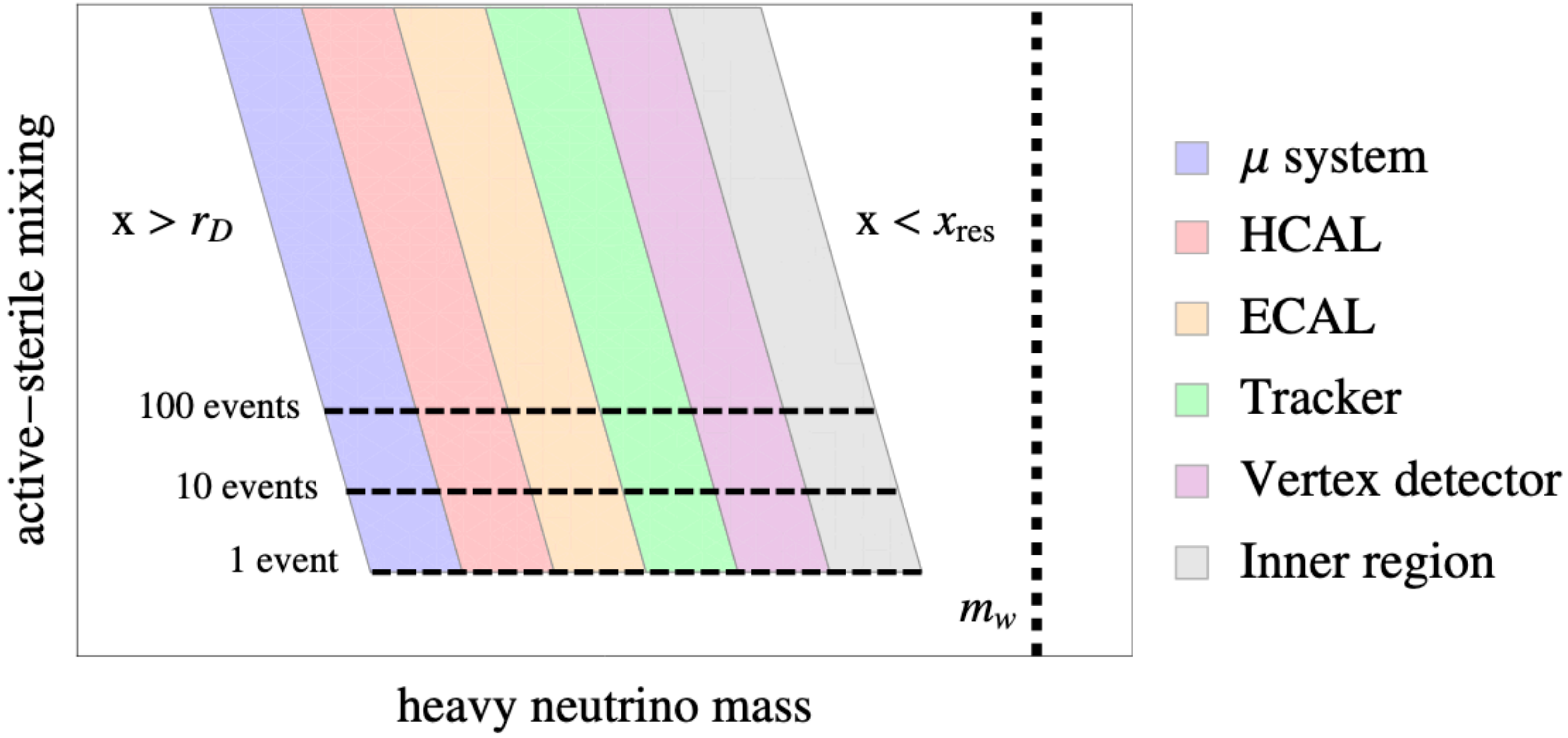
Light LLPs, exotic Higgs decays



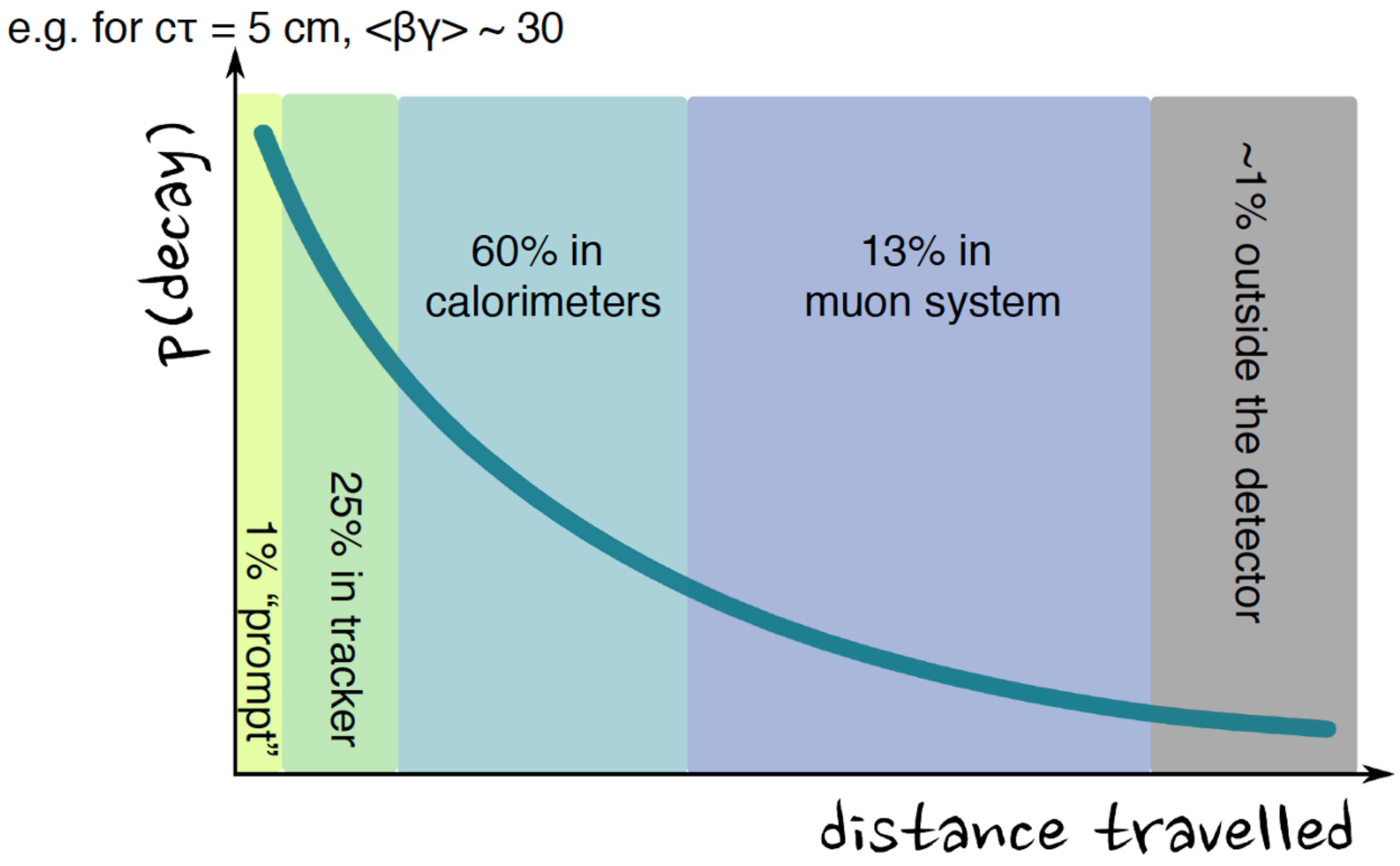
Dark showers

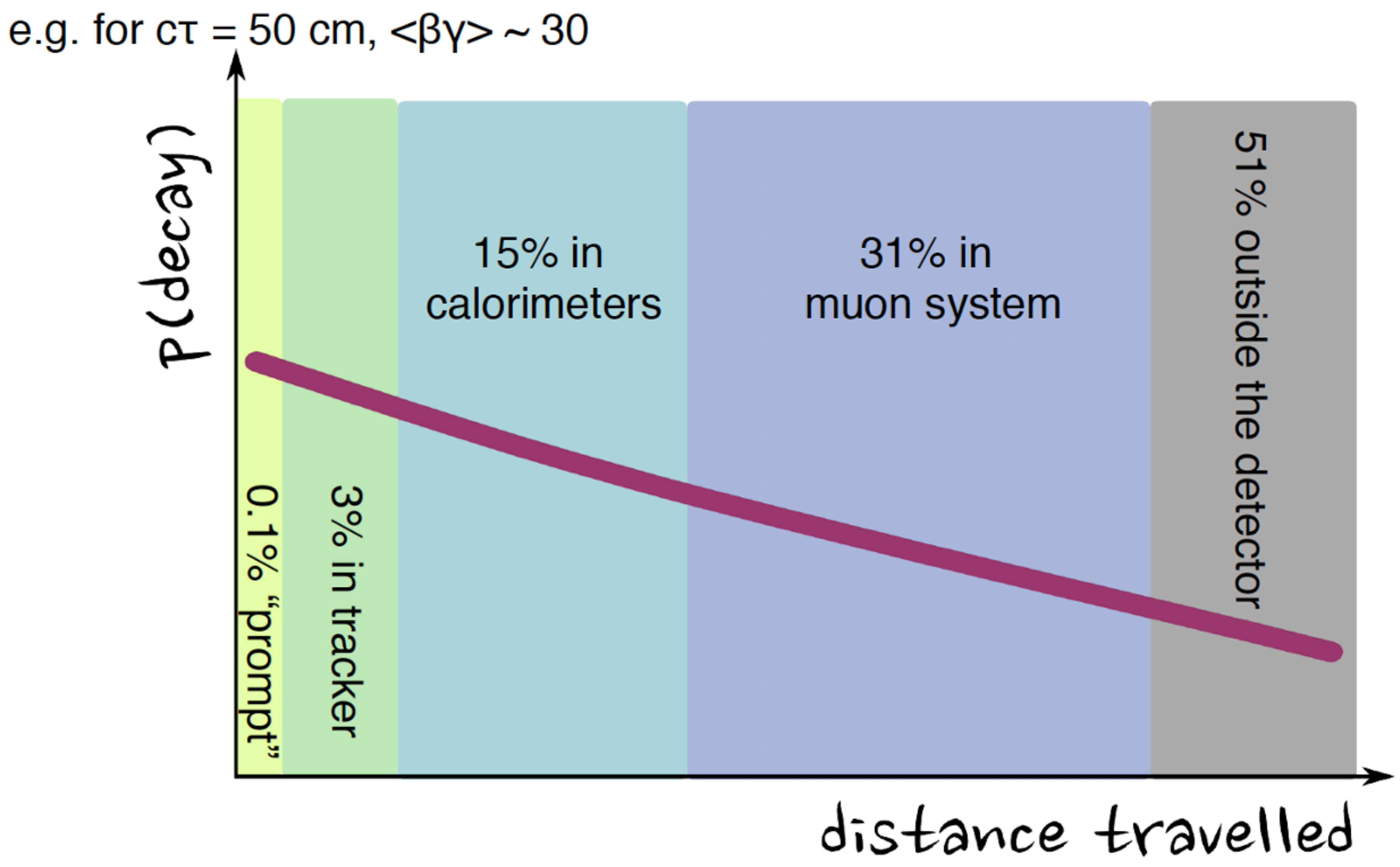


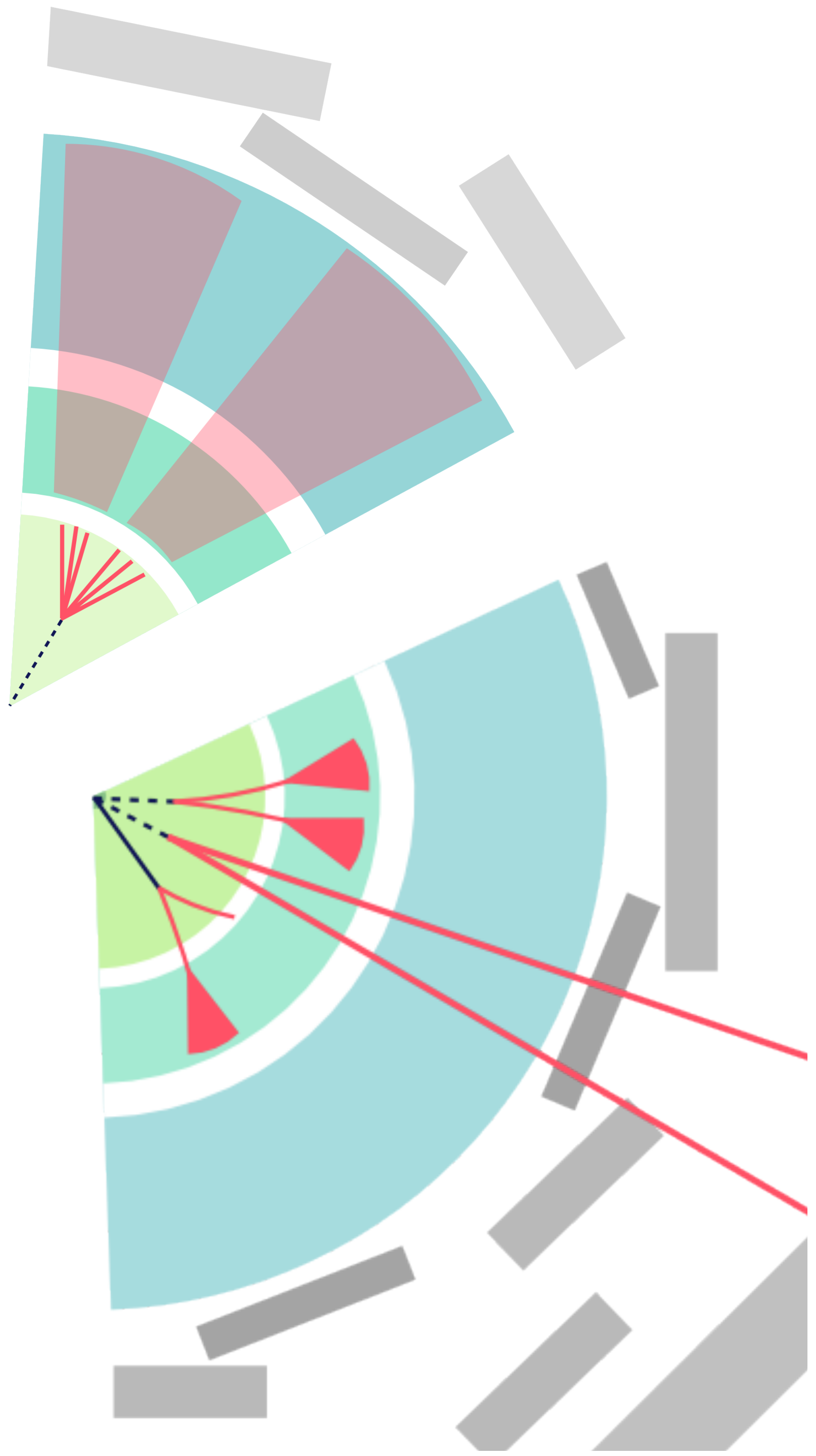
arXiv:1604.02420

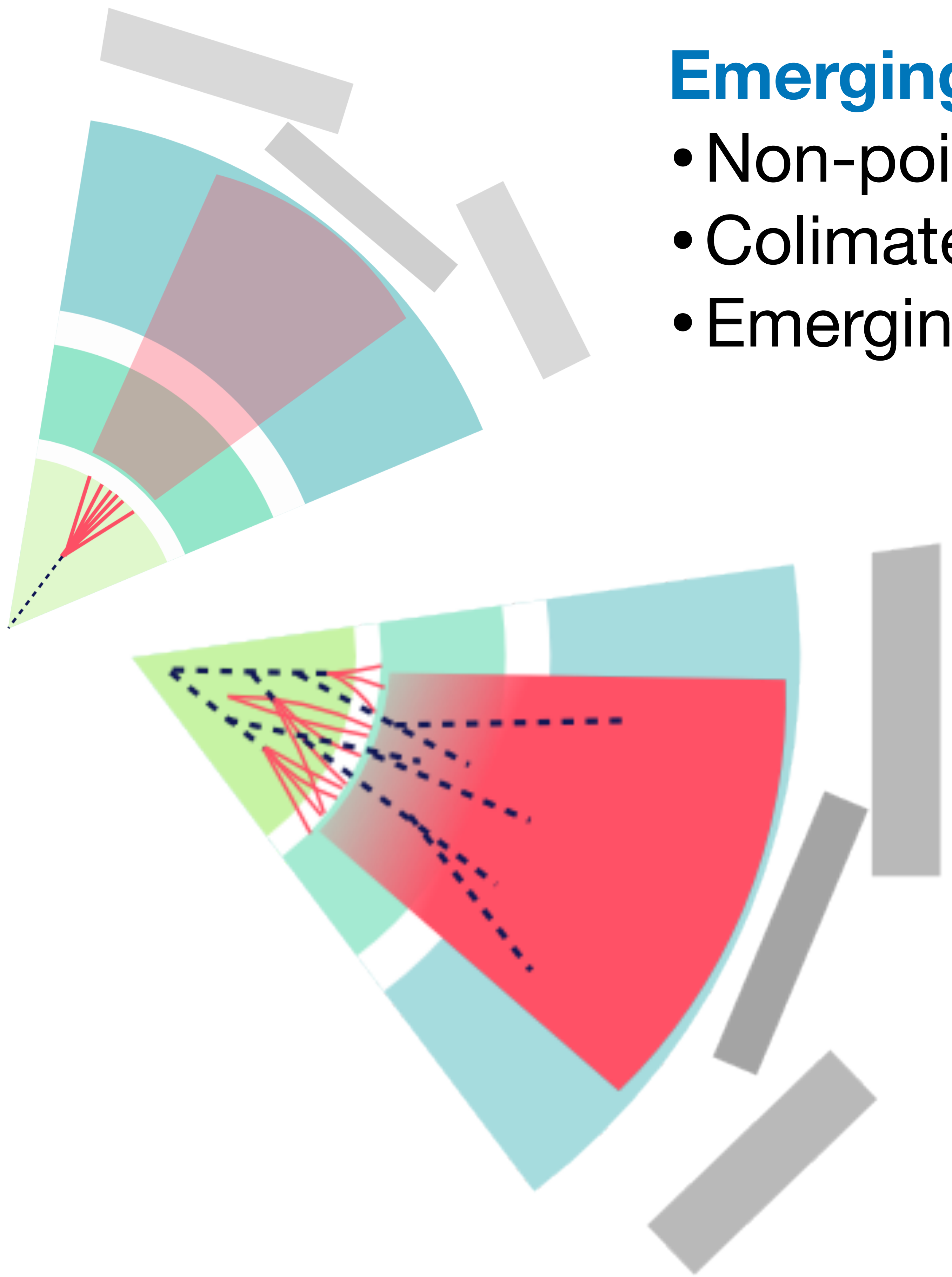


Sensitivity of different detector components to HNL as a function of the mixing parameter and mass


e.g. for cτ = 5 cm, <βγ> ~ 30
P(decay)
1% "prompt"
25% in tracker
60% in calorimeters
13% in muon system
~1% outside the detector
distance travelled

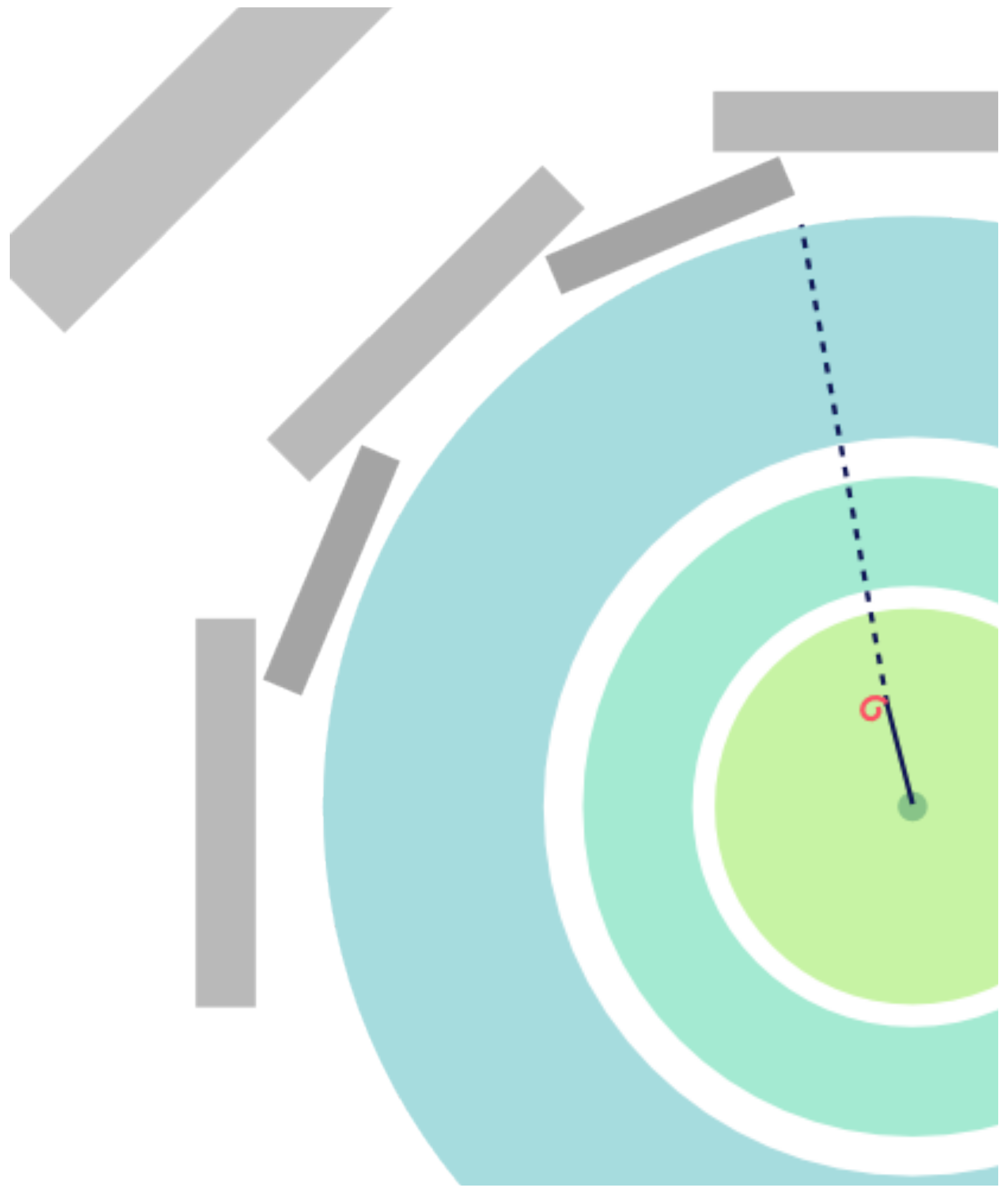

e.g. for cτ = 50 cm, <βγ> ~ 30
P(decay)
0.1% "prompt"
3% in tracker
15% in calorimeters
31% in muon system
51% outside the detector
distance travelled





Emerging/weird

- Non-pointing photons (Calo)
- Colimated objects (Tracker, Calo)
- Emerging jets (Tracker, Calo)



More Tracking component

- Anomalous dE/dx track
- Fractionally charged, Multicharged particles..
- Short (disappearing, kinked) tracks

Displaced/Delayed stuff

- Displaced vertices and tracks (Tracker, Calo)
- Delayed/displaced jets (Tracker, Calo)
- Stopped particle decay (Timing!)