With support from PIA UC VRI, Fondecyt 11220237 and ANID – Millennium Science Initiative Program ICN2019_044

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Long-lived particles

Giovanna Cottin
Pontificia Universidad Católica de Chile
& SAPHIR Millennium Institute

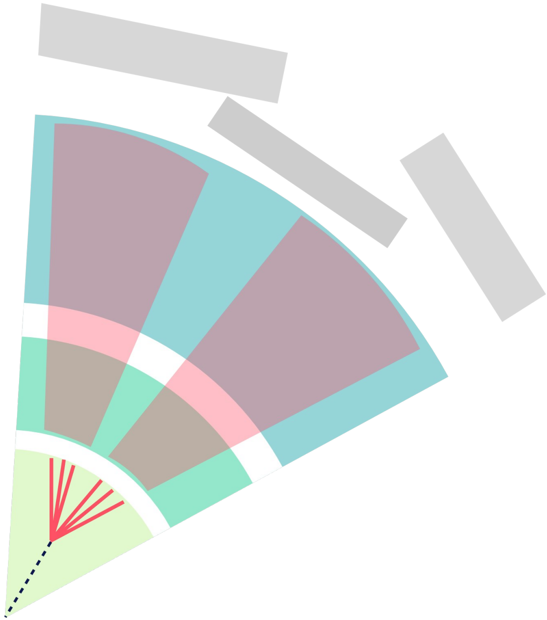


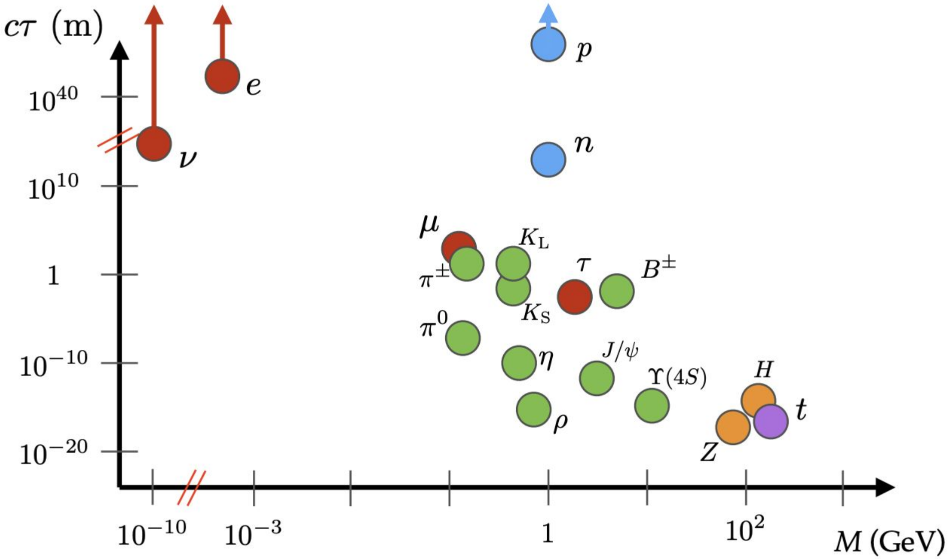
Image from Heather Russel

XV Latin American Symposium on High Energy Physics (SILAFAE)
Mexico City, Cinvestav, November 4th 2024

- What is a long-lived particle?
- Why look for long-lived particles?
- What's the long-lived particle phenomenology @ LHC?
- Why should we keep looking for long-lived particles?

What is a long-lived particle?

Long-lived particles (LLP) can travel macroscopic distances before decaying inside a particle detector. Our world is full of them



Theory motivation: their presence comes from conserved symmetries, small couplings, heavy mediators/hierarchy of mass scales, small phase space. Why a BSM sector shouldn't have some of these?

LLP = "**BSM particle** that dies (gives up all its energy or decays to SM) somewhere in the detector acceptance" J. Beacham

$$c\tau \sim \Gamma^{-1} \gtrsim 0.001 \ [\text{mm}]$$

Image by B.Shuve.
Long-lived Particle Community White Paper, J. Alimena, .. , G.Cottin et al, arXiv:1903.04497

- What is a long-lived particle?
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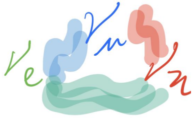
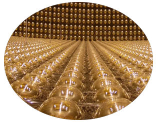
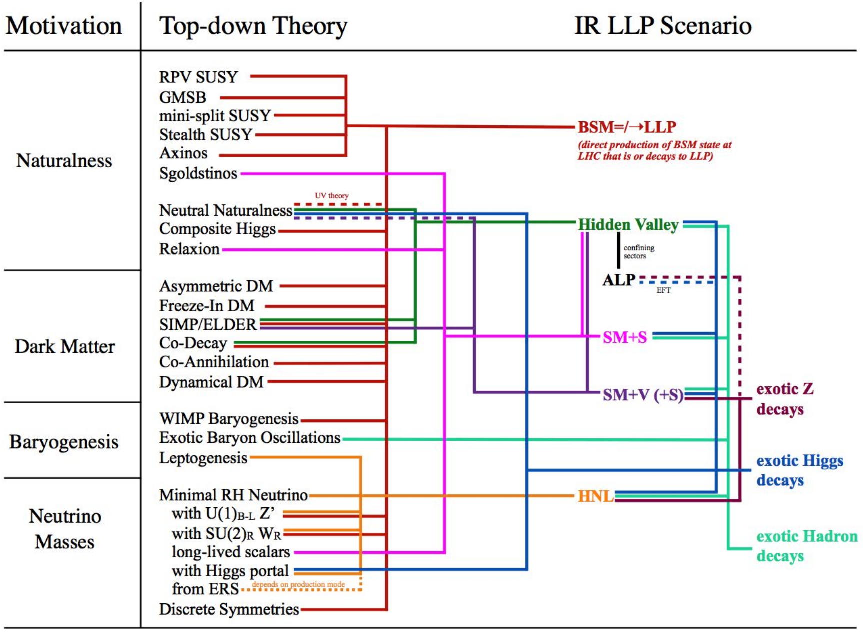
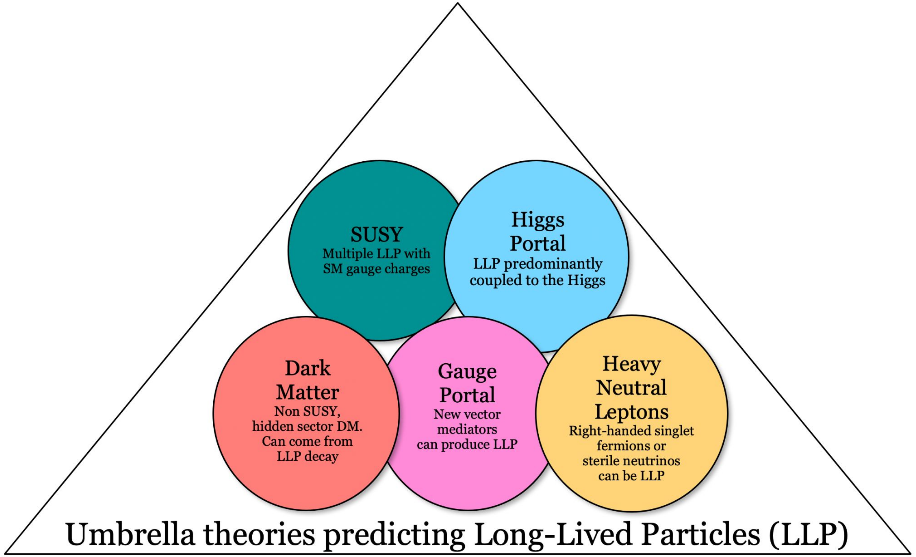
LLPs are predicted in many BSM models





baryons antibaryons





MATHUSLA physics case motivating more complete theoretical models
D. Curtin et al, arXiv:1806.07396

Long-lived Particle Community paper simplified model proposal
J. Alimena, .. , G. Cottin, et al, arXiv:1903.04497

No signs of new physics @ LHC

New physics may be so *feebly* coupled to our Standard Model that their signatures may have been overlooked or miss identified by LHC searches not dedicated to LLPs

LLP

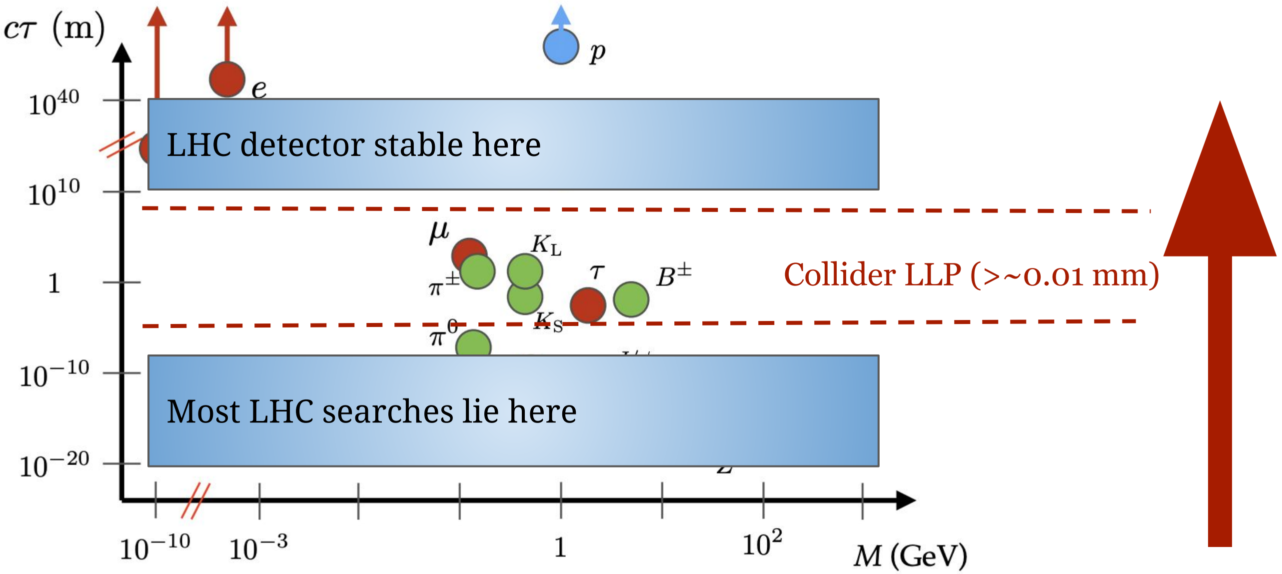
$$c\tau \sim \Gamma^{-1} \gtrsim 0.001 \text{ [mm]}$$

$$\Gamma \sim \underbrace{c^2}_{} \underbrace{\left(\frac{\Delta m}{\Lambda}\right)^n}_{} \underbrace{\Delta m}_{}$$

Three reasons why	Feebly (small) couplings	Large mass hierarchies/ heavy mediators	Small mass difference or “compressed spectra”
Three reasons why is hard	Low rates	Large energies (LHC inaccessible)	Low efficiency (soft particles/limited object reconstruction)

No signs of new physics @ LHC

Are we looking deep in all regions of parameter space?

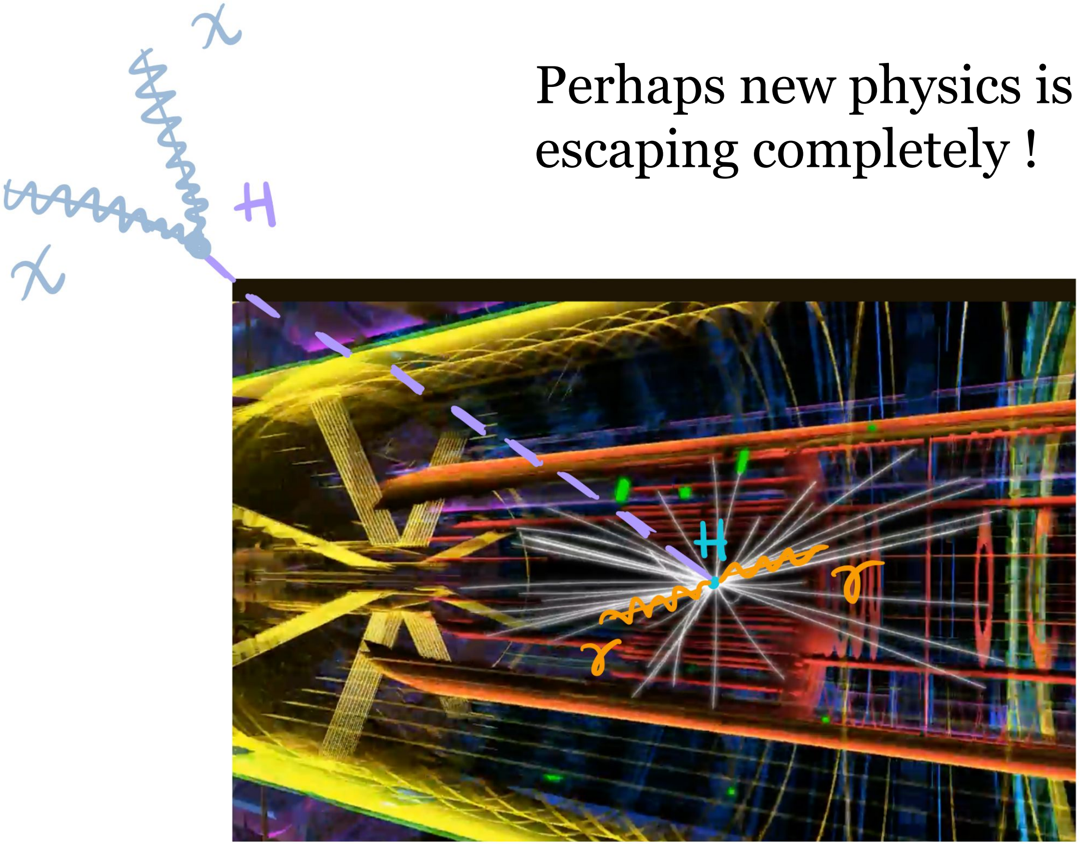


17/201 ATLAS LLP searches (13 TeV results using the full 2015 and 2016 data-set)

https://twiki.cern.ch/twiki/bin/view/AtlasPublic/Winter201713TeV

Image by B.Shuve.
Long-lived Particle Community White Paper, J. Alimena, .. , G.Cottin et al, arXiv:1903.04497

No signs of new physics @ LHC



Perhaps new physics is escaping completely !

“A huge gap” by Meta AI

LHC video

Many LLP efforts worldwide !

LHC-LLP WG: https://lpcc.web.cern.ch/lhc-llp-wg
LLP Community Workshops: https://indico.cern.ch/event/1381368/
LLP Community White Paper: arXiv:1903.04497
LLP repo: https://github.com/llprecasting/recastingCodes
RAMP seminars, including LLP searches: https://indico.cern.ch/category/14155/

CERNCOURIER Reporting on international high-energy physics

Physics ▾ Technology ▾ Community ▾ In focus Magazine

SEARCHES FOR NEW PHYSICS | MEETING REPORT

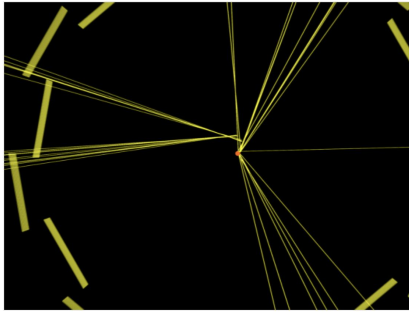
Long-lived particles gather interest

21 July 2021

SEARCHES FOR NEW PHYSICS | MEETING REPORT

A long-lived paradigm shift

27 November 2020



Displaced vertex A simulated CMS collision where a long-lived particle travels a shor
before it decays. Credit: CMS-PHO-EVENTS-2020-002-5

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Searching for long-lived particles beyond the Standard Model at the Large Hadron Collider

as one of the top 1% most-cited papers in IOP Publishing's portfolio of journals from 2020-2022

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Thank you for choosing to publish your work with us.
Juliette Alimena, James Beacham, Martino Borsato, Yangyang Cheng, Xabier Cid Vidal, Giovanna Cottin, David Curtin, Albert De Roeck, Nishita Desai, Jared A Evans, Simon Knapen, Sabine Kraml, Andre Lessa, Zhen Liu, Sascha Mehlhase, Michael J Ramsey-Musolf, Heather Russell, Jessie Shelton, Brian Shuve, Monica Verducci, Jose Zurita et al. (Full list of author names can be found on the article)

Miriam Maus
Publishing Director
IOP Publishing

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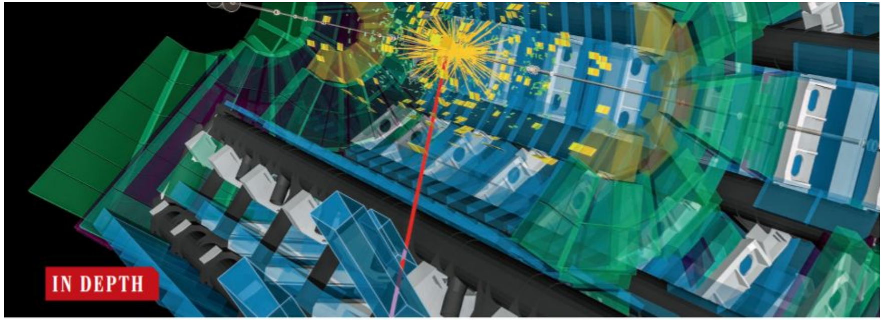
LLP2024: Fourteenth workshop of the Long-Lived Particle Community



In a simulated event, the track of a decay particle called a muon (red), displaced slightly from the center of particle collisions, could be a sign of new physics.

PARTICLE PHYSICS

A hunt for long-lived particles ramps up

The Large Hadron Collider could be making new particles that are hiding in plain sight

By **Adrian Cho**

Are new particles materializing right under physicists' noses and going unnoticed? The world's great atom smasher, the Large Hadron Collider (LHC), could be making long-lived particles that slip through its detectors, some researchers say. Next week, they will gather at the LHC's home, CERN, the European particle physics laboratory near Geneva, Switzerland, to discuss how to capture them. They argue the LHC's next run should emphasize such searches, and some are calling for new detectors that could sniff out the fugitive particles.

It's a push born of anxiety. In 2012, experimenters at the $5 billion LHC discovered simple strategy to look for new particles: Smash together protons or electrons at ever-higher energies to produce heavy new particles and watch them decay instantly into lighter, familiar particles within the huge, barrel-shaped detectors. That's how CMS and its rival detector, A Toroidal LHC Apparatus (ATLAS), spotted the Higgs, which in a trillionth of a nanosecond can decay into, among other things, a pair of photons or two "jets" of lighter particles.

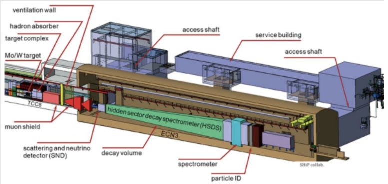
Long-lived particles, however, would zip through part or all of the detector before decaying. That idea is more than a shot in the dark, says Giovanna Cottin, a theorist at National Taiwan University in Taipei. "Almost all the frameworks for beyond-the-standard-model physics predict of subsystems—trackers that trace charged particles, calorimeters that measure particle energies, and chambers that detect penetrating and particularly handy particles called muons—all arrayed around a central point where the accelerator's proton beams collide. Particles that fly even a few millimeters before decaying would leave unusual signatures: kinked or offset tracks, or jets that emerge gradually instead of all at once.

Standard data analysis often assumes such oddities are mistakes and junk, notes Tova Holmes, an ATLAS member from the University of Chicago in Illinois who is searching for the displaced tracks of decays from long-lived supersymmetric particles. "It's a bit of a challenge because the way we've designed things, and the software

SEARCHES FOR NEW PHYSICS | NEWS

SHiP to chart hidden sector

3 May 2024

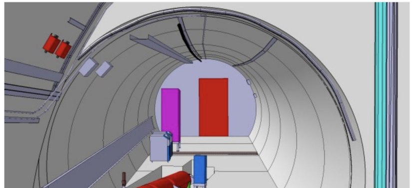


Full speed ahead Layout of the SHiP experiment, with the target on the left and the experim
the ECN3 hall. Credit: SHiP collab.

FASER: CERN approves new experiment to look for long-lived, exotic particles

The experiment, which will complement existing searches for dark matter at the LHC, will be operational in 2021

7 MARCH, 2019 | By Cristina Agrigoroae



Adding your recasting code

This is an open repository and if you have developed a code for recasting a LLP analysis, we encourage you to include it here. Please contact llp-recasting@googlegroups.com and we will provide you with the necessary information for including your code.

Repository Structure

The repository folder structure is organized according to the type of LLP signature and the corresponding analysis and authors:

- Displaced Vertices
  - 13 TeV ATLAS Displaced Vertex plus MET by ALessa
  - 13 TeV ATLAS Displaced Vertex plus MET by GCottin
  - 8 TeV ATLAS Displaced Vertex plus jets by GCottin
- Heavy Stable Charged Particles
  - 8 TeV CMS HSCP
  - 13 TeV ATLAS HSCP
- Disappearing Tracks NEW
- Displaced Jets

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LHC-LLP searches can target different lifetimes using different parts of the detectors. Detection usually requires special triggers and reconstruction

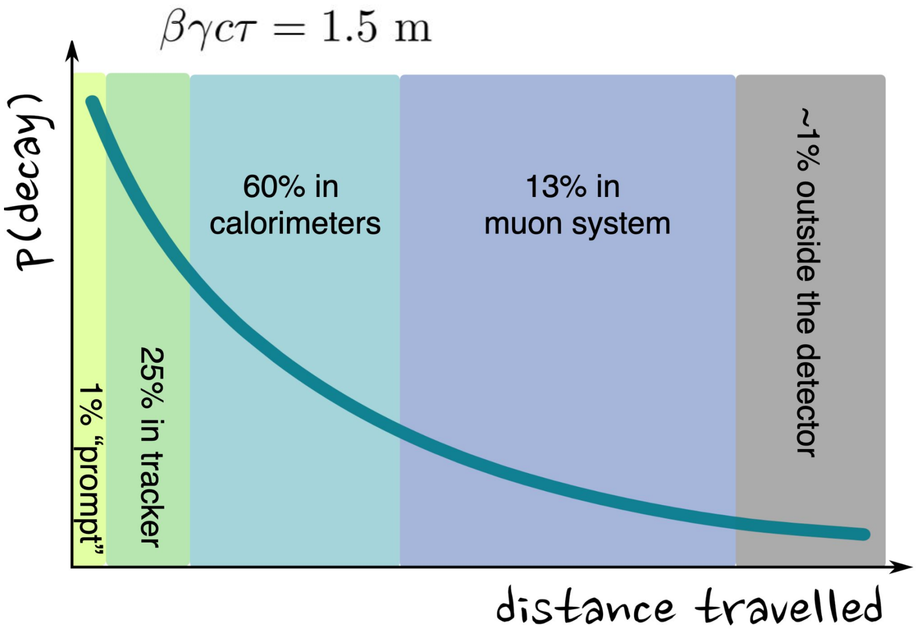
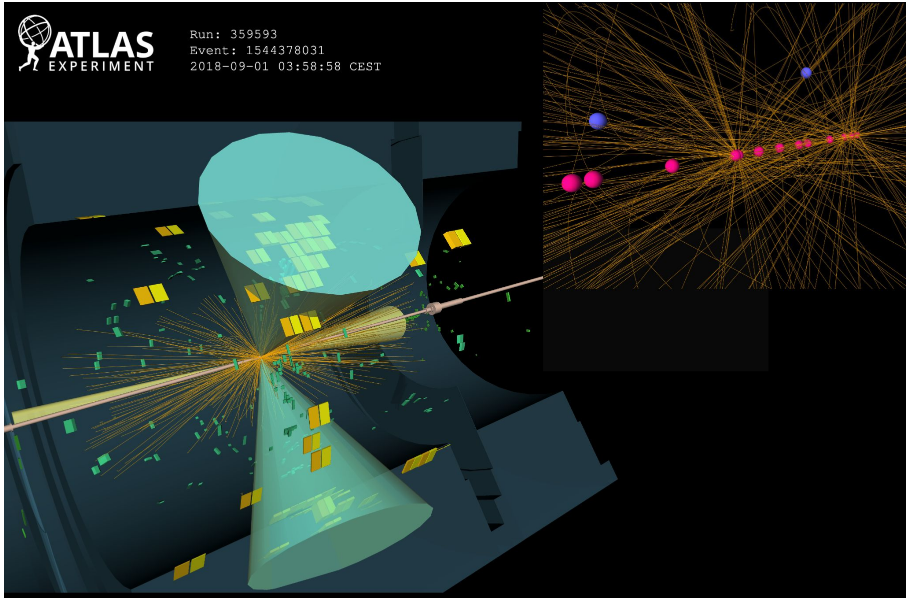


Image by Heather Russel (based on ATLAS geometry)
Long-lived Particle Community Workshop, 2017



ATLAS Event Display with Displaced Vertices

Depending on where the LLP decays, it's mass and which quantum numbers it has, this will give rise to different exotic collider signatures

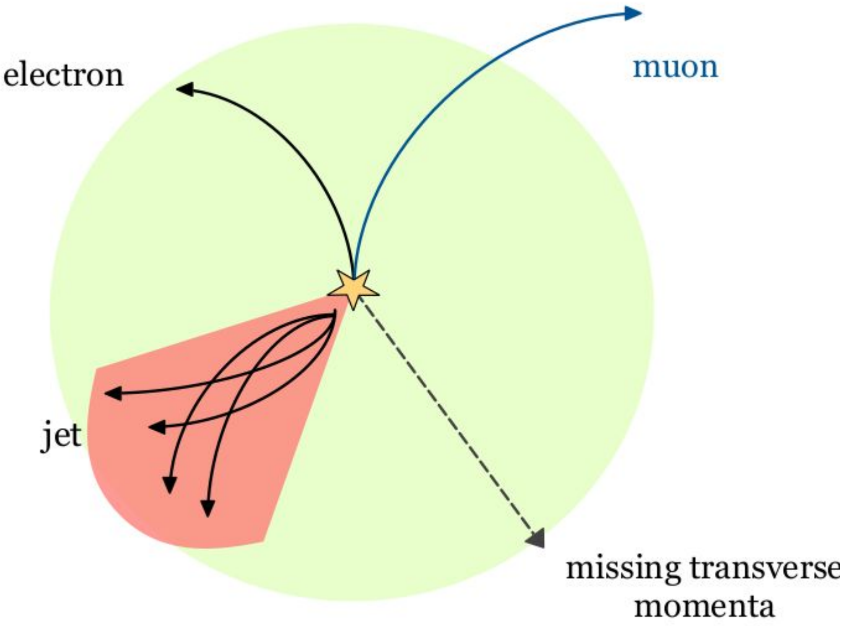
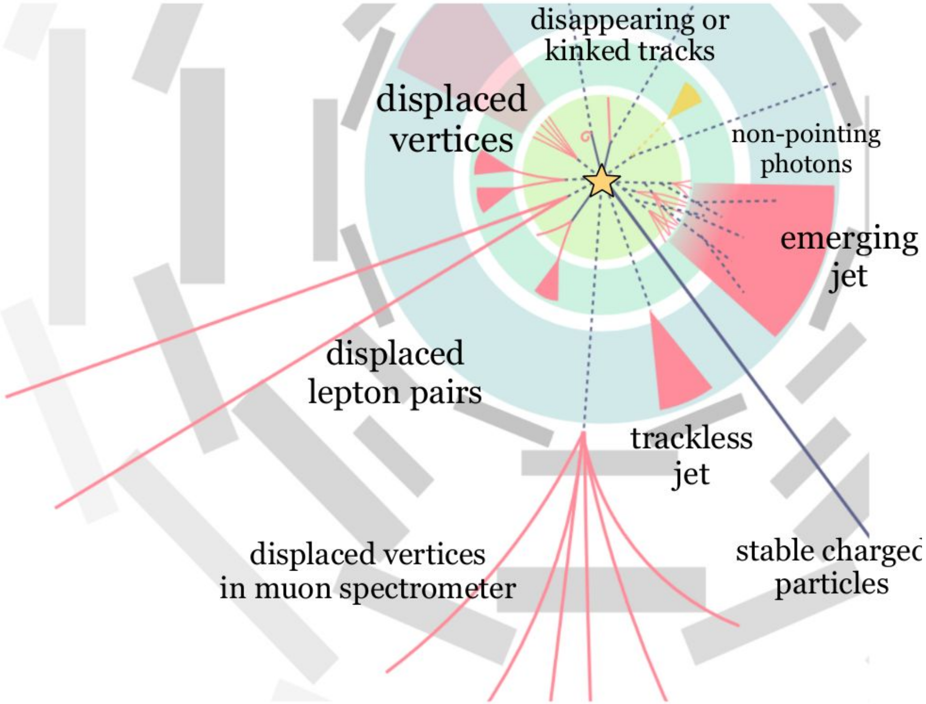


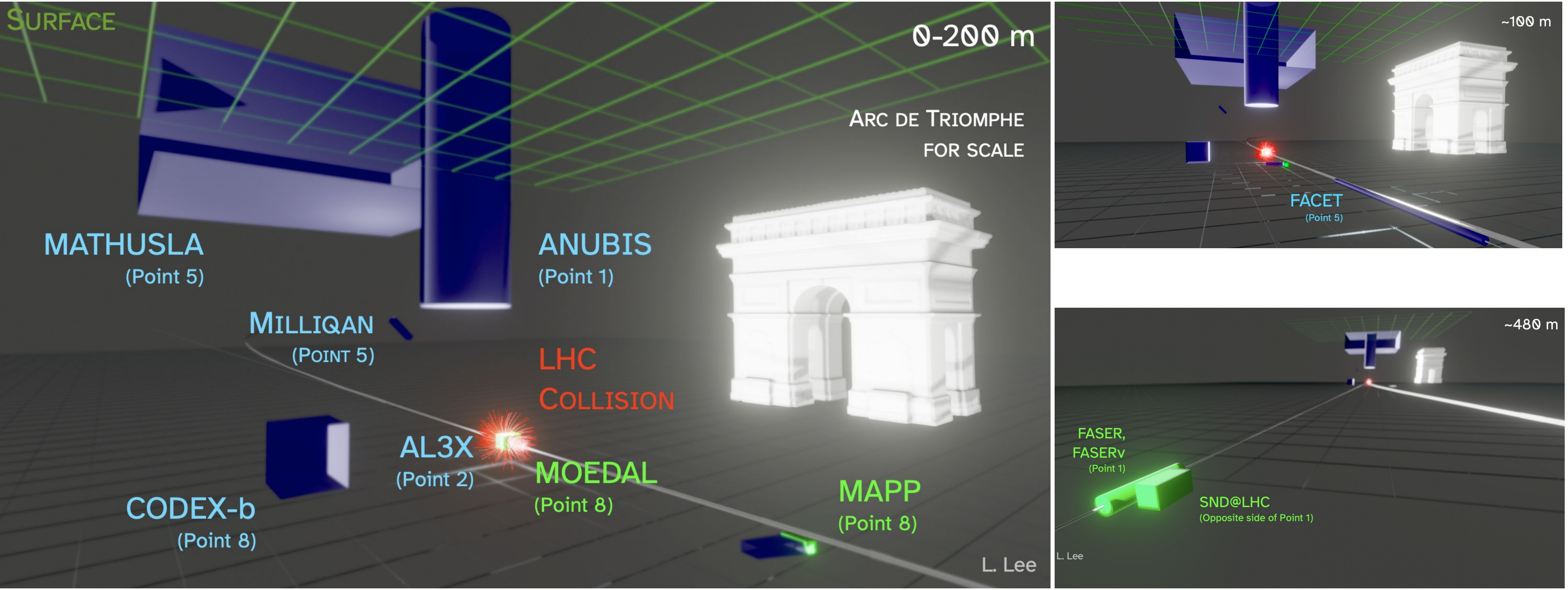
Image by G. Cottin



LLP Image adapted from Heather Russel.
Long-lived Particle Community White Paper, J. Alimena, .. , G. Cottin, et al, [arXiv:1903.04497]

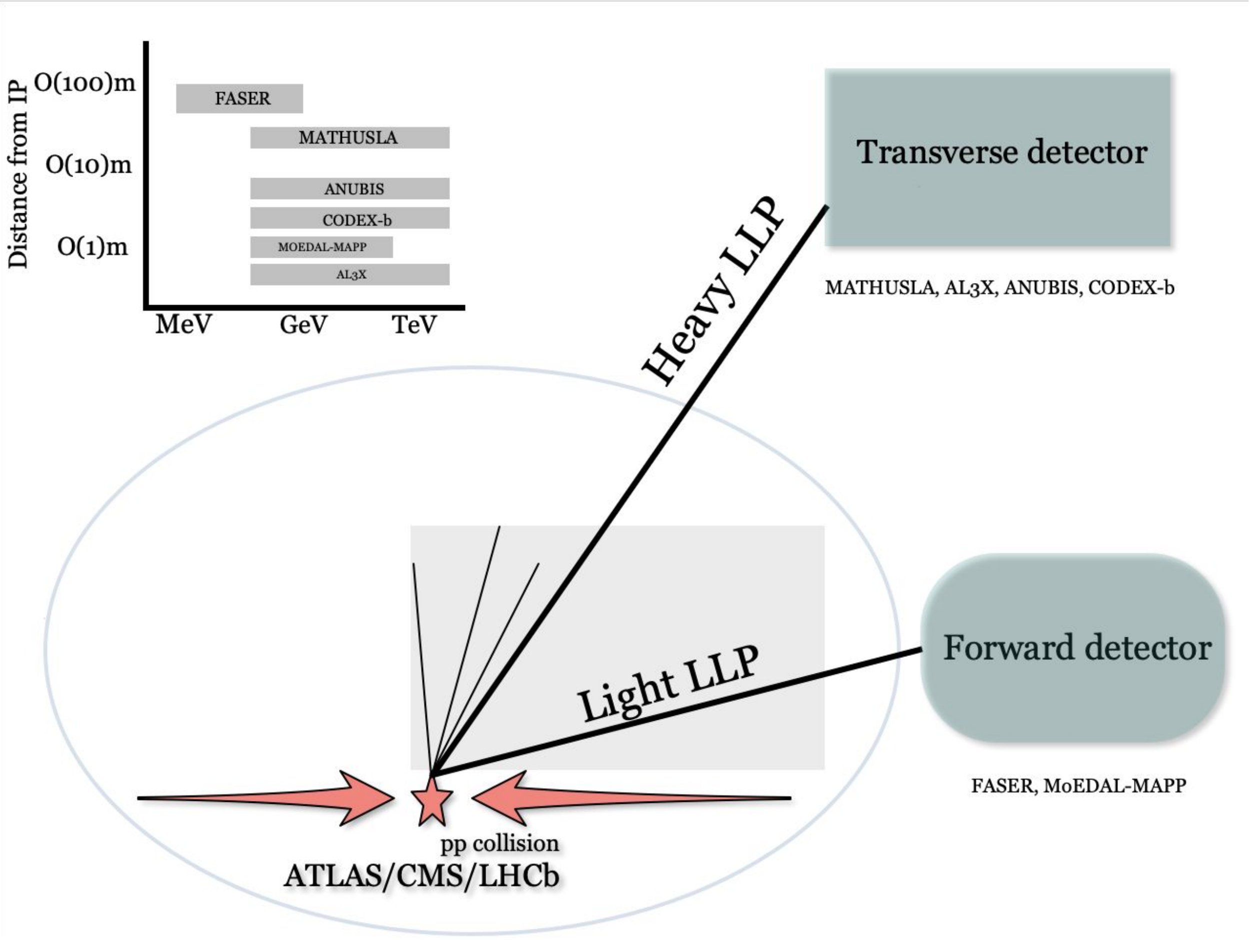
New approved/proposed LHC-LLP detector experiments

All these experiments have the potential to search for LLPs with different geometrical acceptances



Slide from [L. Lee @ LHCPC2021]

Many LLP detectors needed to target complementary regions in LLP model parameter space

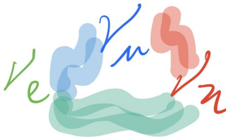


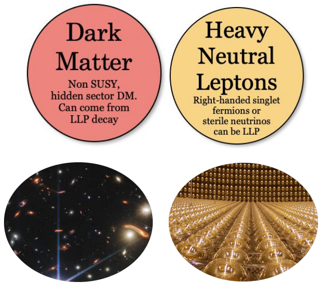
General purpose detectors are "complex" (large angular acceptance, many sub-detectors to exploit LLP signature)/ no LLP triggers/challenging triggers, large backgrounds, difficult-non-efficient reconstruction

Dedicated detectors are "simpler" (no trigger, targeted reconstruction, are cheaper), limited/zero bkg/smaller angular acceptance

Image by G. Cottin inspired by M.Citron's talk at LLPXII

LHC-LLP phenomenology in selected models



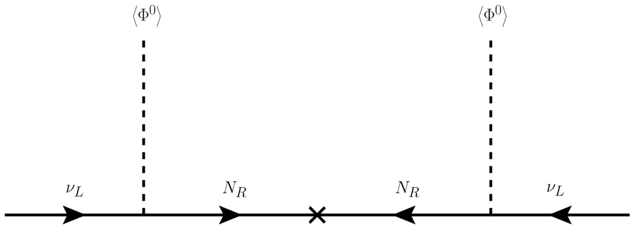


Theoretical motivation: Several models that explain neutrino masses and dark matter predict LLPs

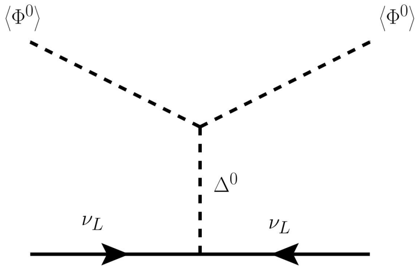
$$\mathcal{L}_5 = \frac{C_5^{\ell\ell'}}{\Lambda}\left[\Phi\cdot\overline{L_\ell^c}\right]\left[L_{\ell'}\cdot\Phi\right] + \text{H.c.}$$

Seesaw
P. Minkowski, Phys. Lett. 67B (1977)
R. N. Mohapatra and G. Senjanovic, Phys. Rev. Lett. 44 (1980)
J. Schechter and J. W. F. Valle, Phys. Rev. D22, 2227 (1980)
Diagrams from S. Centelles, R. Srivastava, J.W.F. Valle, Phys.Lett.B 781 (2018)

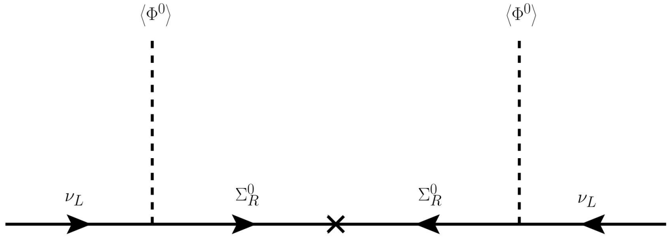
At tree level, the d=5 Weinberg operator can be generated in three ways (type-I,II and III seesaw)



$N_R \equiv F(1,1,0)$



$\Delta^0 \equiv S(1,3,1)$



$\Sigma_R^0 \equiv F(1,3,0)$

At one-loop, there are many more possibilities, where neutrino masses and dark matter (DM) might have a common origin

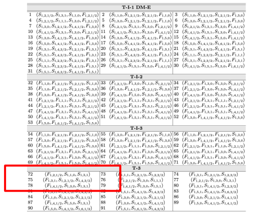
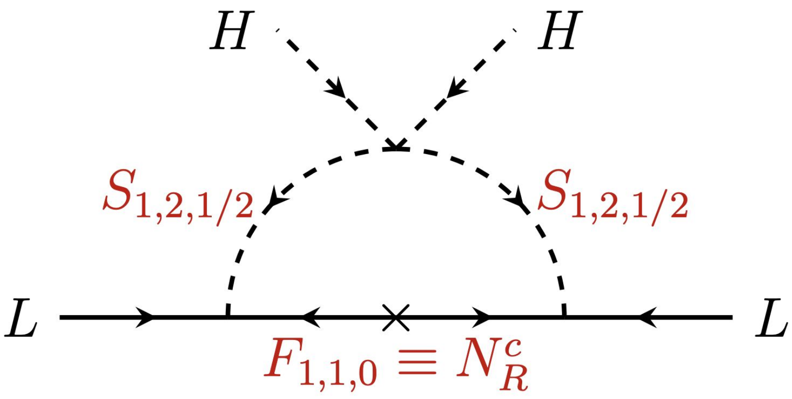


Table 8: DM models with exits (DM-E) which need a stabilizing symmetry to give an acceptable WIMP candidate.

Scotogenic Model

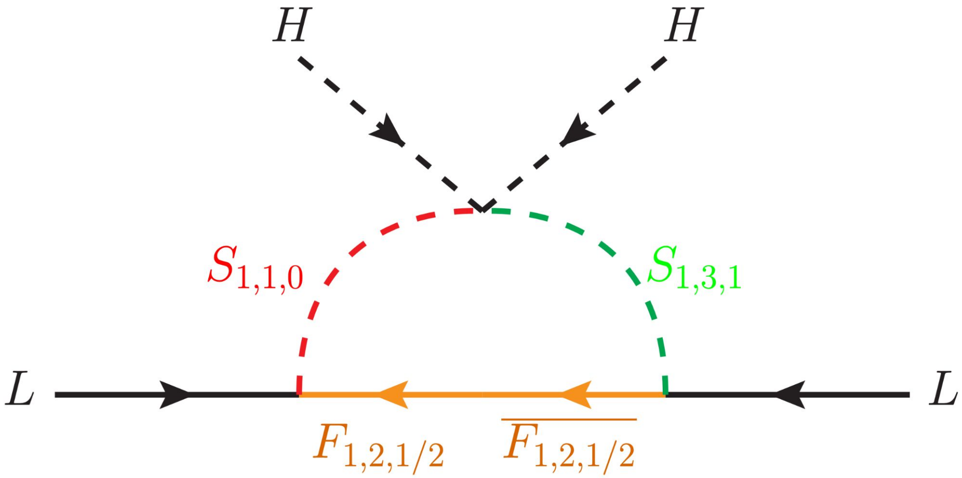
E. Ma, Phys.Rev.D 73 (2006) 077301

LLP phenomenology in Scotogenic model in
A. G. Hessler, A. Ibarra, E. Molinaro, S. Vogl, JHEP 01 (2017)
I. M. Ávila, G. Cottin, M. A. Díaz, J.Phys.G 49 (2022)
SmodelS2 in G. Alguero et al, JHEP 08 (2022) 068



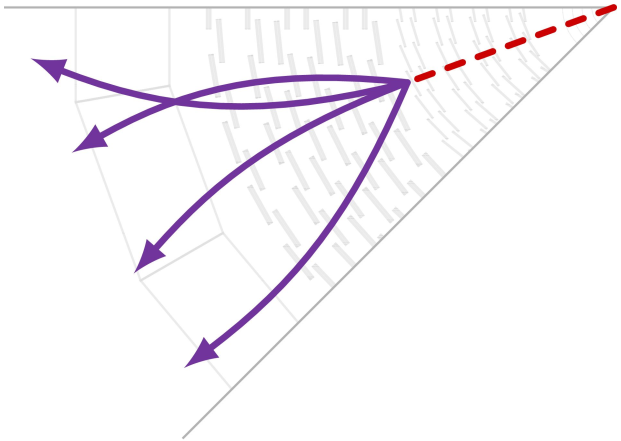
Scalar-Singlet-Triplet (SST) Model

C. Arbeláez, G. Cottin, J. C. Helo, M. Hirsch, T. B. de Melo, arXiv:2408.03364



LLP Phenomenology for Heavy Neutral Leptons (Neutral LLP)

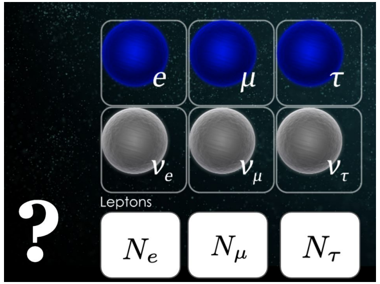
Image from https://tikz.net/bsm_longlived/



Minimal Heavy Neutral Lepton (HNL) model

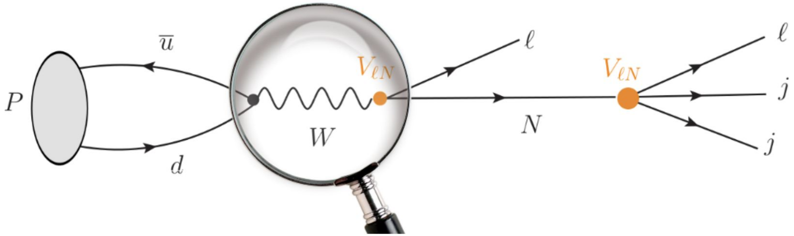
- HNLs (fermionic singlets) motivated by seesaw models
- HNLs mix with SM neutrinos
- Can be automatically long-lived! $\Gamma \sim G_F^2 |V_{lN}|^2 m_N^5$

See reviews for HNL phenomenology
M. Drewes, Int.J.Mod.Phys.E 22 (2013) 1330019, arXiv:1303.6912
F. Deppisch, P. S. Bhupal Dev, Apostolos Pilaftsis, New J.Phys. 17 (2015) 7, 075019, arXiv:1502.06541
Y. Cai, T. Han, Tong Li, R. Ruiz, Front.in Phys. 6 (2018) 40, arXiv: :1711.02180
The Present and Future Status of Heavy Neutral Leptons, Snowmass, arXiv: 2203.08039



$$\mathcal{L}_{\text{min}} = -\frac{g}{\sqrt{2}} V_{\ell N}\, \overline{\ell}\gamma^\mu P_L N\, W^\dagger_\mu - \frac{g}{2\cos\theta_W} U^*_{\ell i} V_{\ell N}\, \overline{\nu_i}\gamma^\mu P_L N\, Z_\mu + \text{h.c.}$$

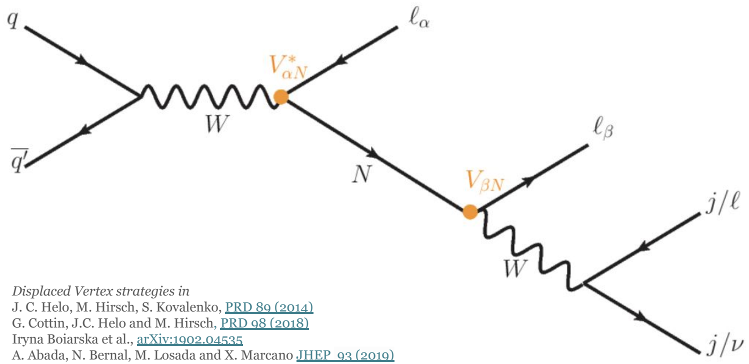
$m_N < m_B$



$\mathcal{O}(\text{GeV})$ K. Bondarenko, et al, JHEP 11 (2018) 032

Diagrams by R. Beltrán

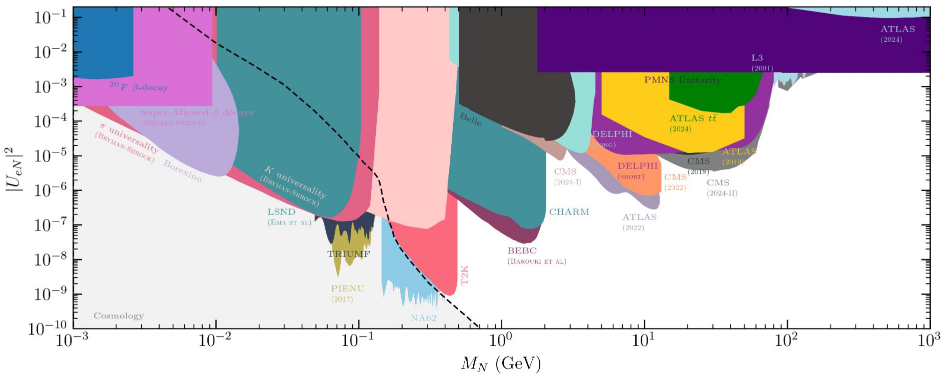
$m_B < m_N < m_W$

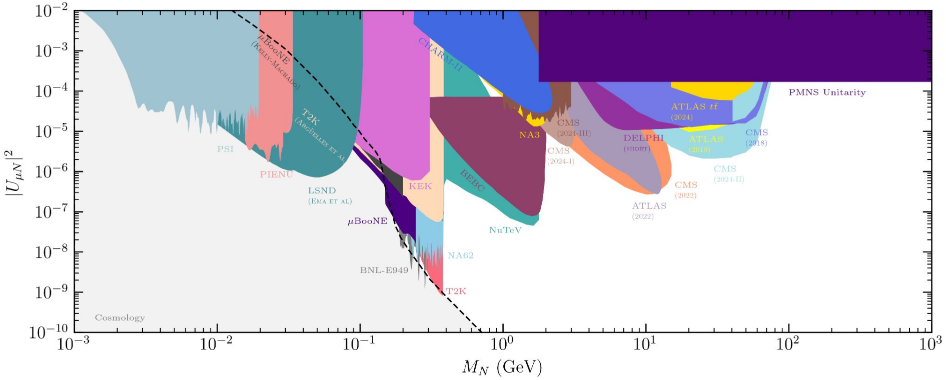


Displaced Vertex strategies in
J. C. Helo, M. Hirsch, S. Kovalenko, PRD 89 (2014)
G. Cottin, J.C. Helo and M. Hirsch, PRD 98 (2018)
Iryna Boiarska et al., arXiv:1902.04535
A. Abada, N. Bernal, M. Losada and X. Marcano JHEP 93 (2019)
M. Drewes, J. Hajer, JHEP 70 (2020)

Experimental Landscape

E. Fernandez-Martinez, et. al, [2304.06772](2304.06772), https://github.com/mhostert/Heavy-Neutrino-Limits





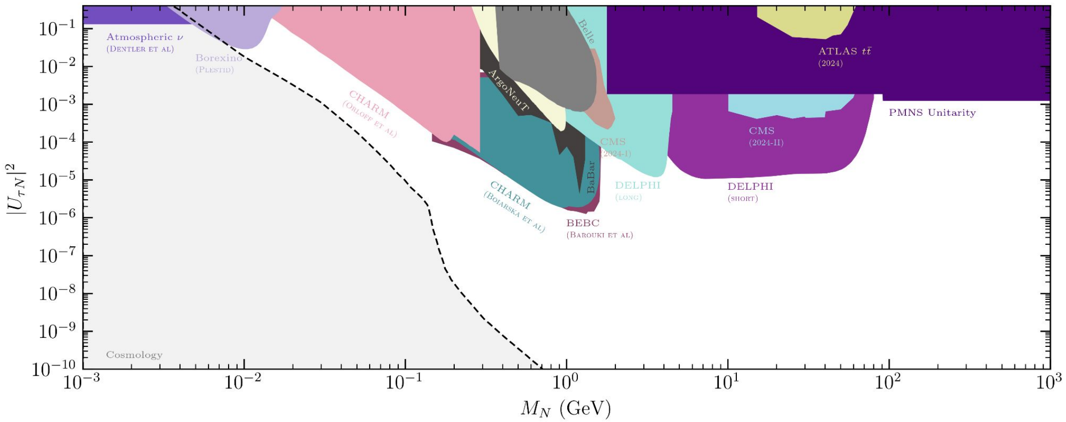
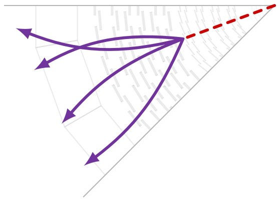
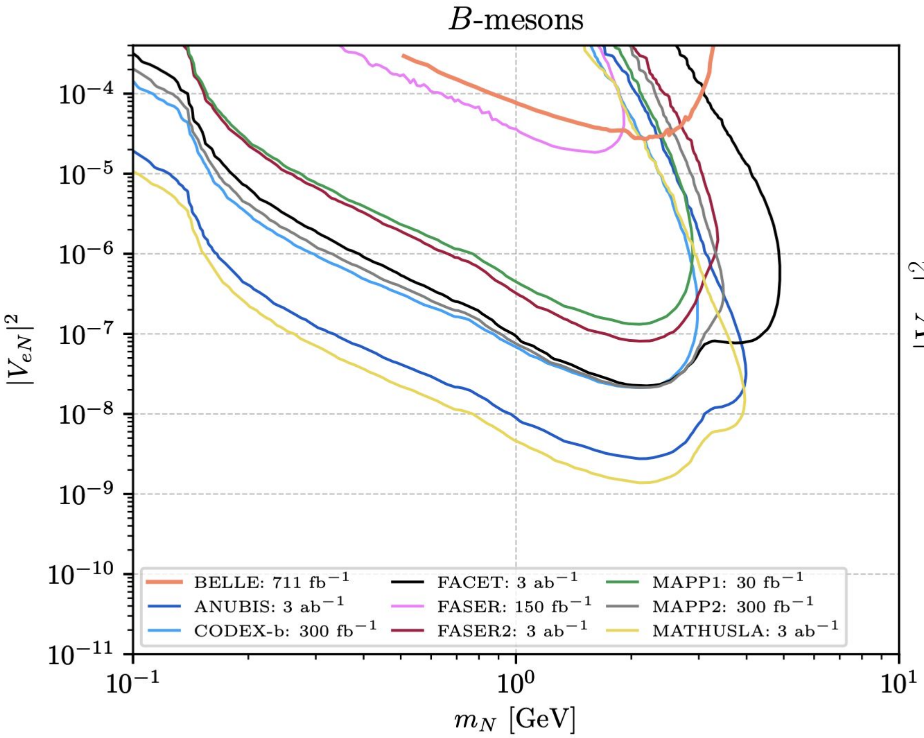
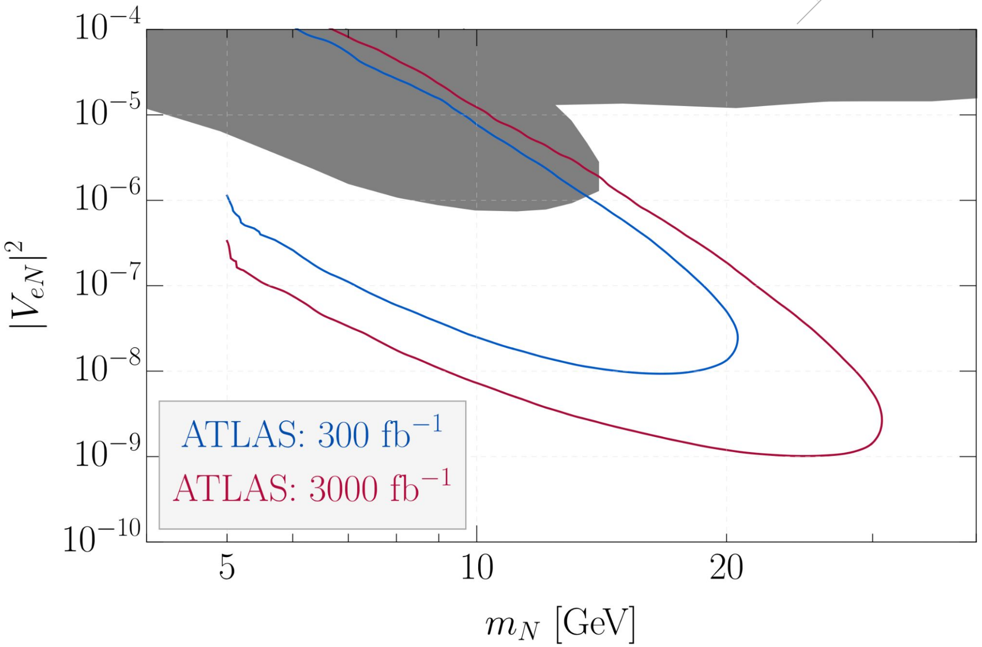


Image from https://tikz.net/bsm_longlived/

Sensitivity prospects in the Minimal Heavy Neutral Lepton (HNL) model with displaced activity







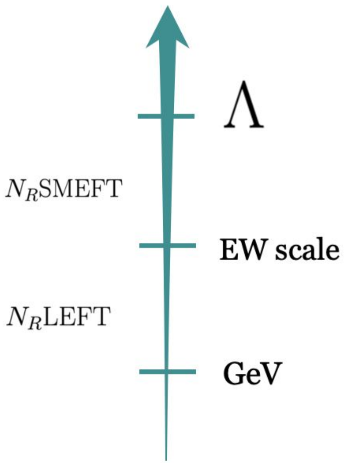
Reinterpretation of searches for long-lived particles from meson decays
R. Beltrán, G. Cottin, M. Hirsch, A. Titov, Z. S. Wang, JHEP 05 (2023) 031

Displaced Vertex strategy optimized in
R. Beltrán, G. Cottin, J.C. Helo, M. Hirsch, A. Titov, Z.S. Wang, JHEP 01 (2022) 044

Beyond the minimal HNL model

- We can study HNLs systematically in an EFT approach, with NRO which are suppressed by a new physics scale
- HNL production and/or decay can be dominated by the operator

$$\mathcal{L}_{N_R\mathrm{SMEFT}} = \mathcal{L}_{\mathrm{SM}+N_R} + \sum_{d\geq 5} \frac{1}{\Lambda^{d-4}} \sum_i c_i^{(d)} \mathcal{O}_i^{(d)}$$



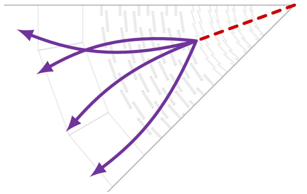
Example of *d*=6 four-fermion operators with *pairs* of HNL

Name	Structure
$\mathcal{O}_{dN}$	$(\overline{d_R}\gamma^\mu d_R)\,(\overline{N_R}\gamma_\mu N_R)$
$\mathcal{O}_{uN}$	$(\overline{u_R}\gamma^\mu u_R)\,(\overline{N_R}\gamma_\mu N_R)$
$\mathcal{O}_{QN}$	$(\overline{Q}\gamma^\mu Q)\,(\overline{N_R}\gamma_\mu N_R)$
$\mathcal{O}_{eN}$	$(\overline{e_R}\gamma^\mu e_R)\,(\overline{N_R}\gamma_\mu N_R)$
$\mathcal{O}_{NN}$	$(\overline{N_R}\gamma_\mu N_R)\,(\overline{N_R}\gamma_\mu N_R)$
$\mathcal{O}_{LN}$	$(\overline{L}\gamma^\mu L)\,(\overline{N_R}\gamma_\mu N_R)$

First developed in
F. del Aguila, S. Bar-Shalom, A. Soni, J. Wudka, 0806.0876 (Phys.Lett.B670, 2008)
A. Aparici, K. Kim, A. Santamaria, J. Wudka, 0904.3244 (Phys.Rev.D80, 2009)
Basis for d<=9 in
H.-L. Li, Z. Ren, M.-L. Xiao, J.-H. Yu, Y.-H. Zheng, 2105.09329

HNLs in EFT with LLPs at the LHC
(d=5) A. Caputo, et al, JHEP 06 (2017)
(NRLEFT, singleN) Jordy de Vries, et al, JHEP 03 (2021)
(NRSMEFT, pair N) G. Cottin, et al, JHEP 01 (2021)
(NRSMEFT, single N) R. Beltrán, et al, JHEP 09 (2022)
(NRLEFT, pair N) R. Beltrán, et al, JHEP 01 (2023)
(NRLEFT), E. Fernandez-Martinez, et. al, JHEP09(2023)

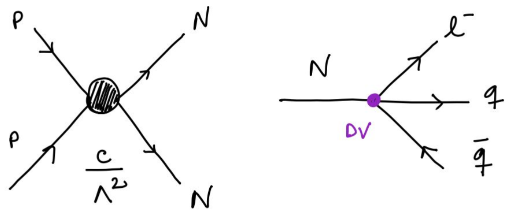
Image from https://tikz.net/bsm_longlived/

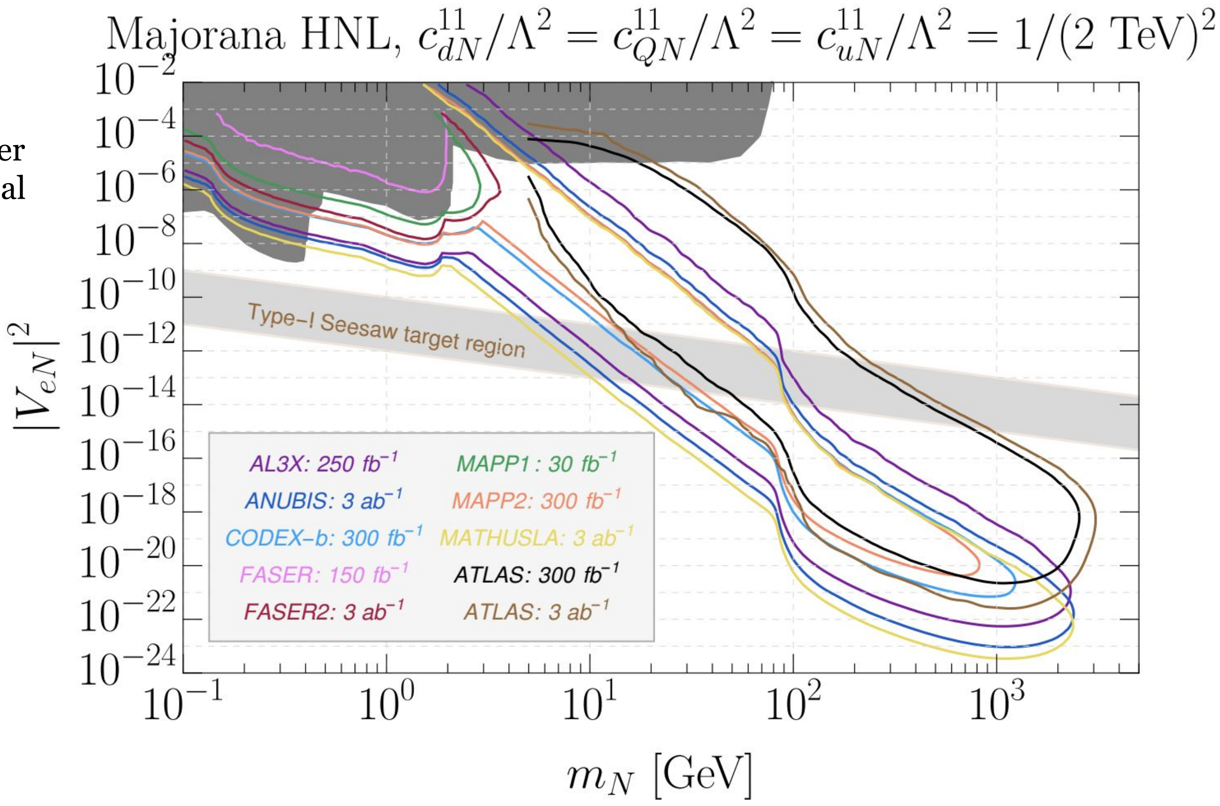


Sensitivity prospects beyond the Minimal HNL model with displaced activity

G. Cottin, J. C. Helo, M. Hirsch, A. Titov, Z. S. Wang, JHEP 09 (2021) 039

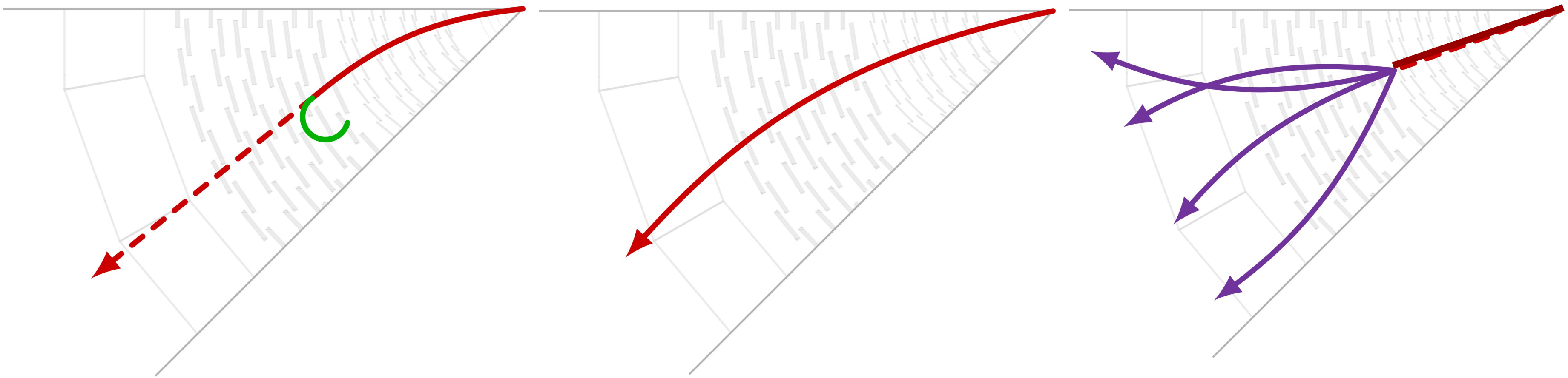
- Production dominated by the operator
- HNLs decay only via mixing
- DV strategy proposed for ATLAS tracker
- Probability of displaced decay in fiducial volume in far detectors





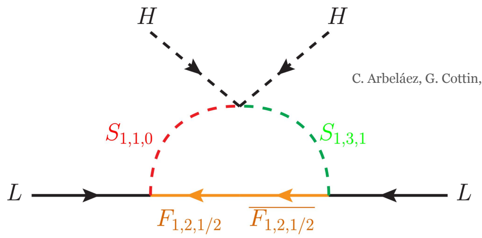
LLP Phenomenology for Scotogenic-like dark matter models (multi-charged LLPs)

Image from https://tikz.net/bsm_longlived/
modified by G.Cottin



Scalar-Singlet-Triplet (SST) Model

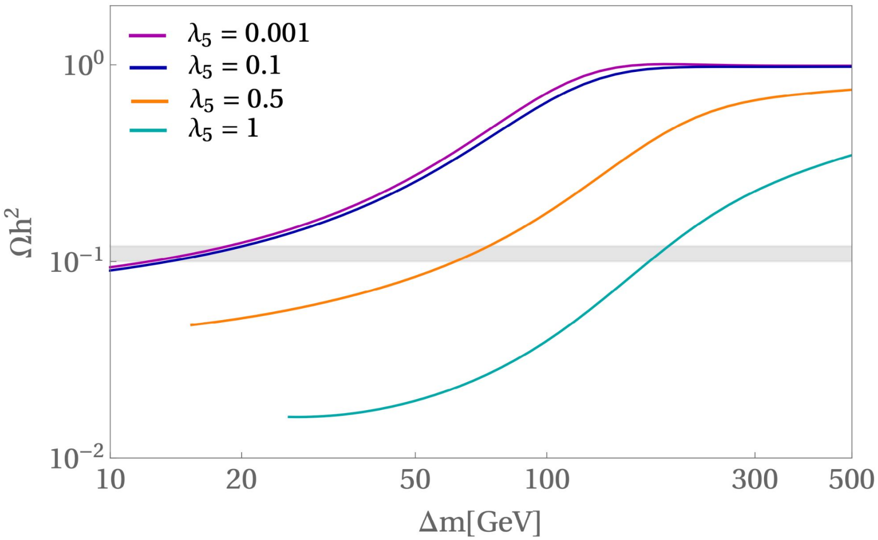
- Neutrino masses at 1-loop
- DM candidate is a combination of singlet+triplet
- Predicts a doubly-charged long-lived particle
  (in the co-annihilation region)



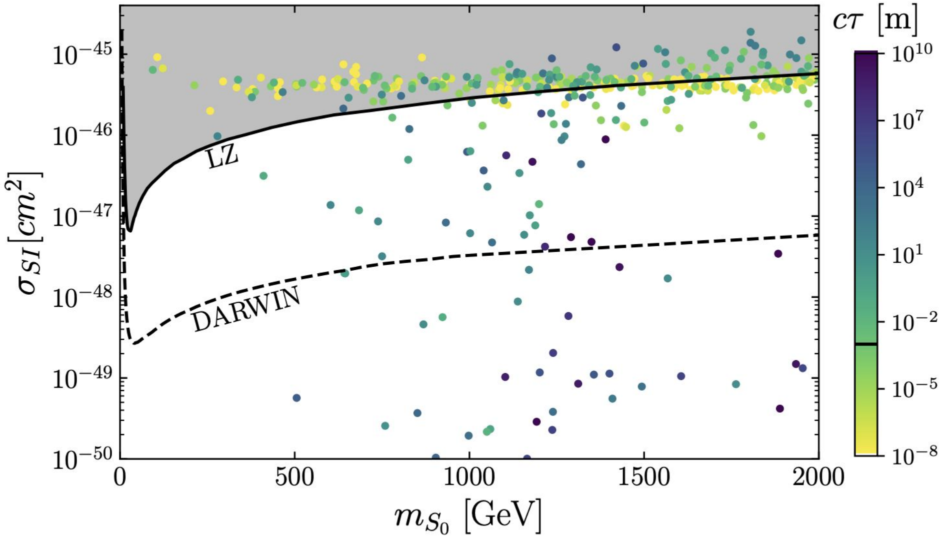
Coannihilations in
K. Griest and D. Seckel, Phys. Rev.D 43 (1991)
M. Klasen, C. E. Yaguna, et al, JCAP 04, 044 (2013)
1-loop neutrino mass models with dark matter in
C. Arbeláez, et al, JHEP 08 (2022) 023
LLP phenomenology for SST model in
C. Arbeláez, G. Cottin, J. C. Helo, M. Hirsch, T. B. de Melo, arXiv:2408.03364

Relic density favours points with small mass splittings between scalar singlet and triplet

$$\lambda_5 H H S_1 S_3^\dagger \qquad \Delta m \equiv m_{t^{++}} - m_{S_0}$$



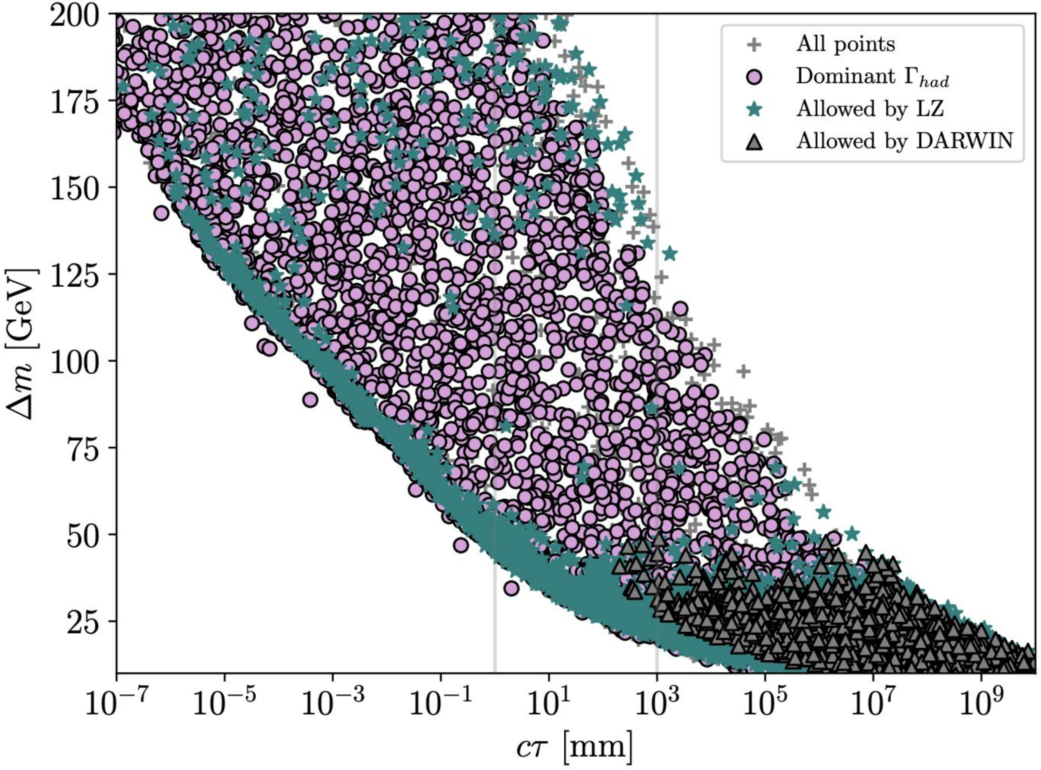
Points in this region that pass future direct detection bounds have small decay width for t^{++}



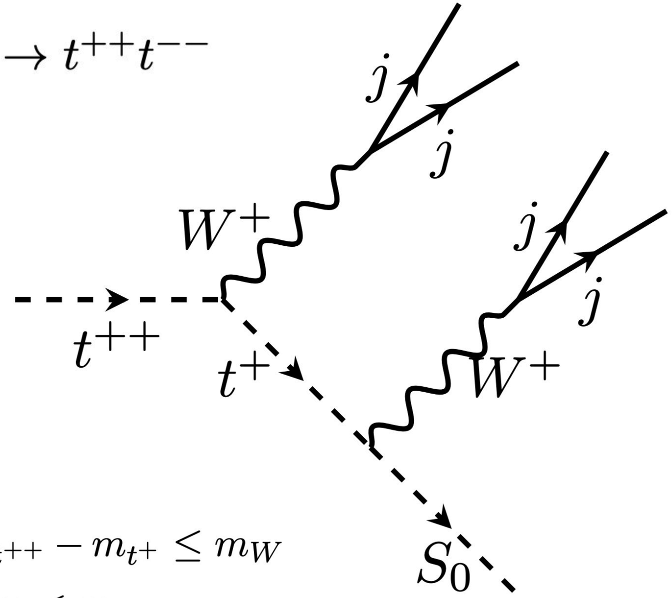
Model from 1-loop classification in C. Arbeláez, R. Cepedello, J.C. Helo, M. Hirsch and S. Kovalenko, JHEP 08 (2022) 023
LLP phenomenology in C. Arbeláez, G. Cottin, J. C. Helo, M. Hirsch, T. B. de Melo, arXiv:2408.03364

The presence of the scalar triplet will give rise to signals (potentially very different) from the scotogenic model

$$S_3 = \begin{pmatrix} t^+/\sqrt{2} & t^{++} \\ t^0 & -t^+/\sqrt{2} \end{pmatrix}$$



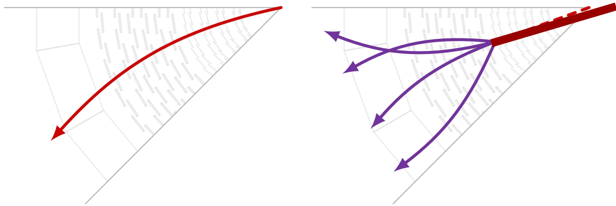
$$pp \to t^{++}t^{--}$$



$$m_{t^{++}} - m_{t^{+}} \leq m_W$$

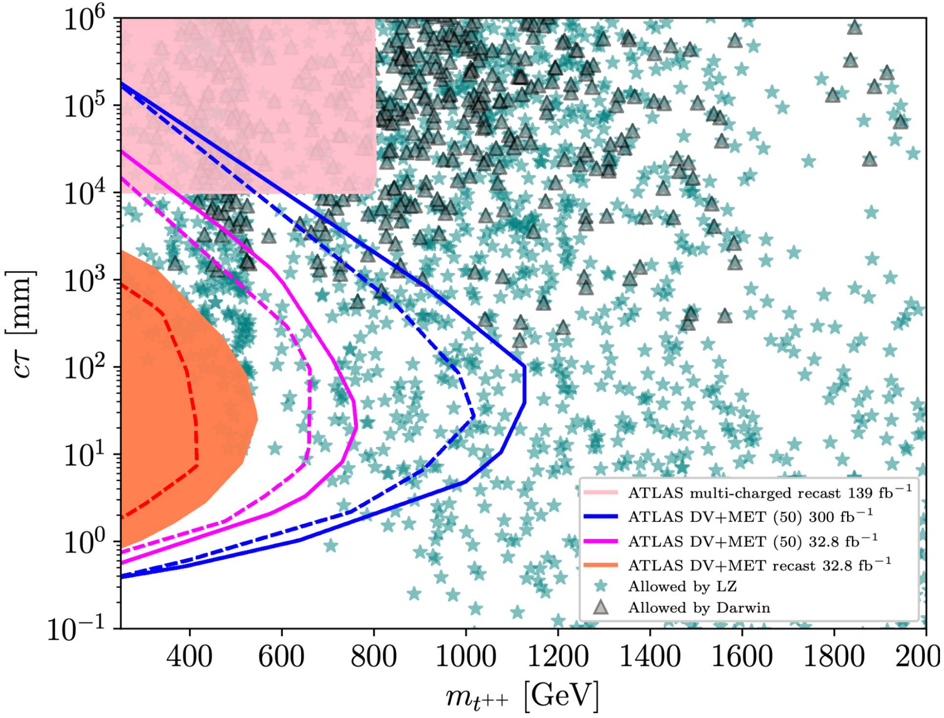
$$\Delta m < m_W$$

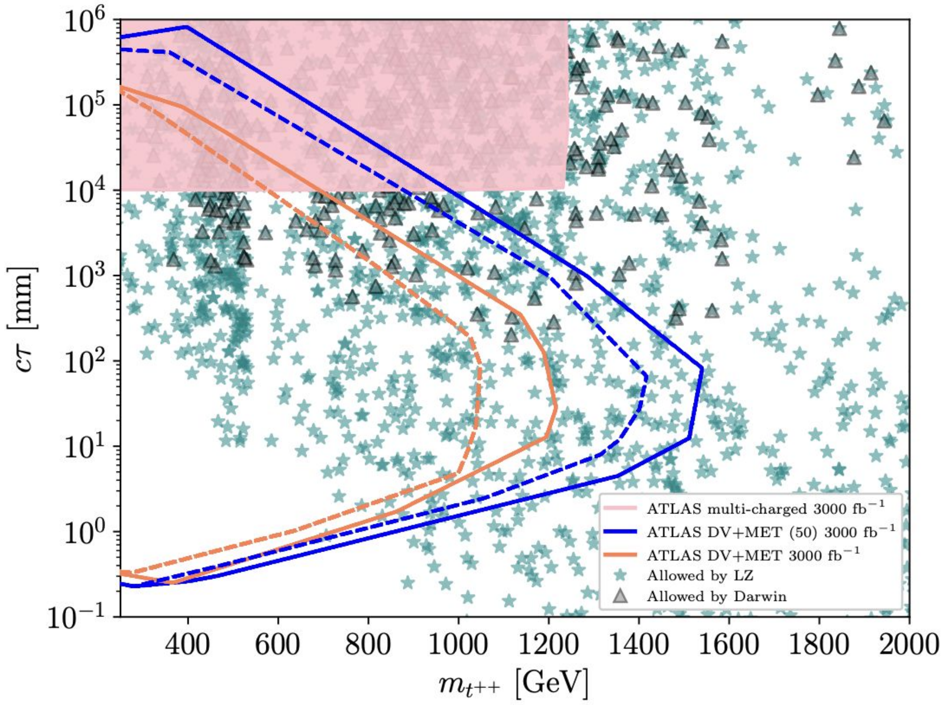
Image from https://tikz.net/bsm_longlived/
modified by G.Cottin



Sensitivity prospects for SST model with displaced activity

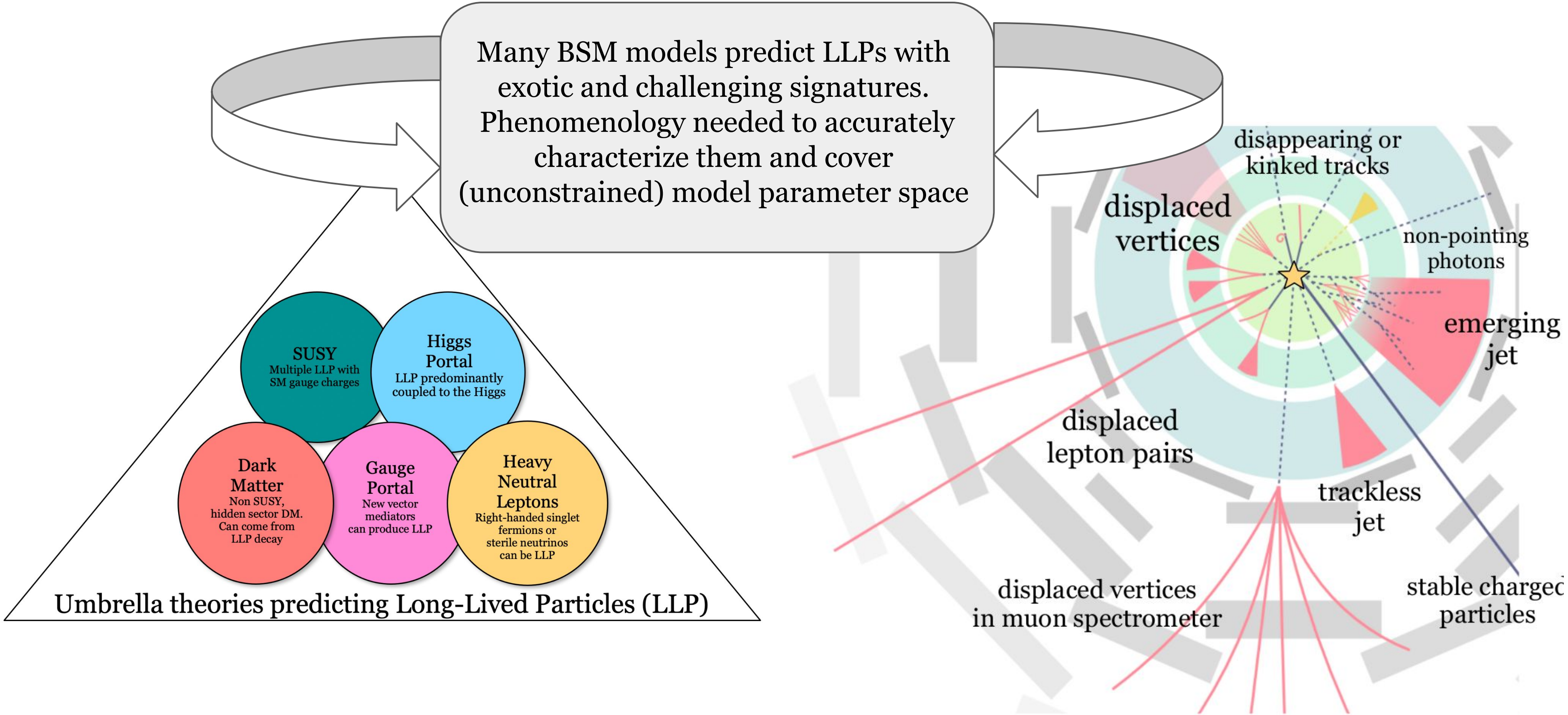
LLP phenomenology in C. Arbeláez, G. Cottin, J. C. Helo, M. Hirsch, T. B. de Melo, arXiv:2408.03364





- What is a long-lived particle?
- Why look for long-lived particles?
- What’s the long-lived particle phenomenology @ LHC?
- Why should we keep looking for long-lived particles?

I presented examples motivated by neutrino masses and dark matter



See MATHUSLA physics case motivating theoretical models, D. Curtin et al, Rept.Prog.Phys. 82 (2019)
See simplified model classification in LLP Community White Paper, J. Alimena, et al J.Phys.G 47 (2020) 9, 090501

LLP Image adapted from Heather Russel

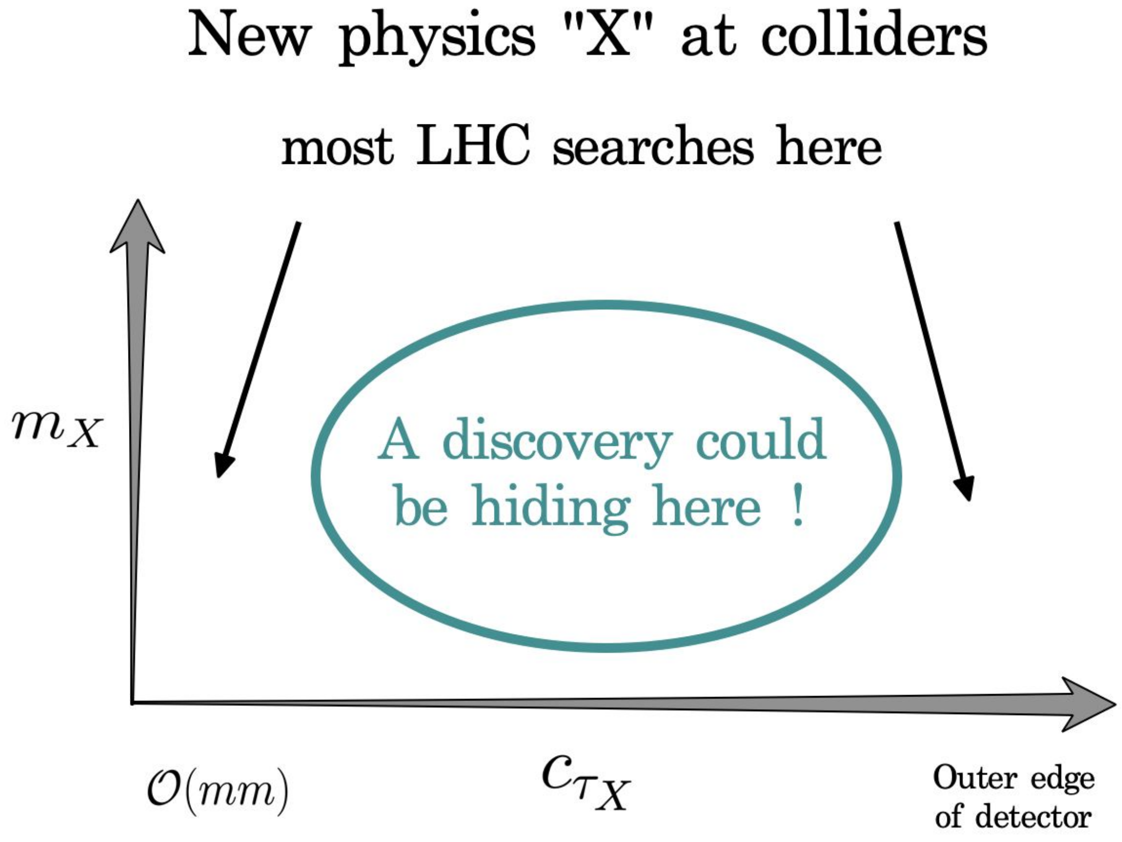


Image reproduced from J. Beacham

The search for new physics: a tale of cross frontiers

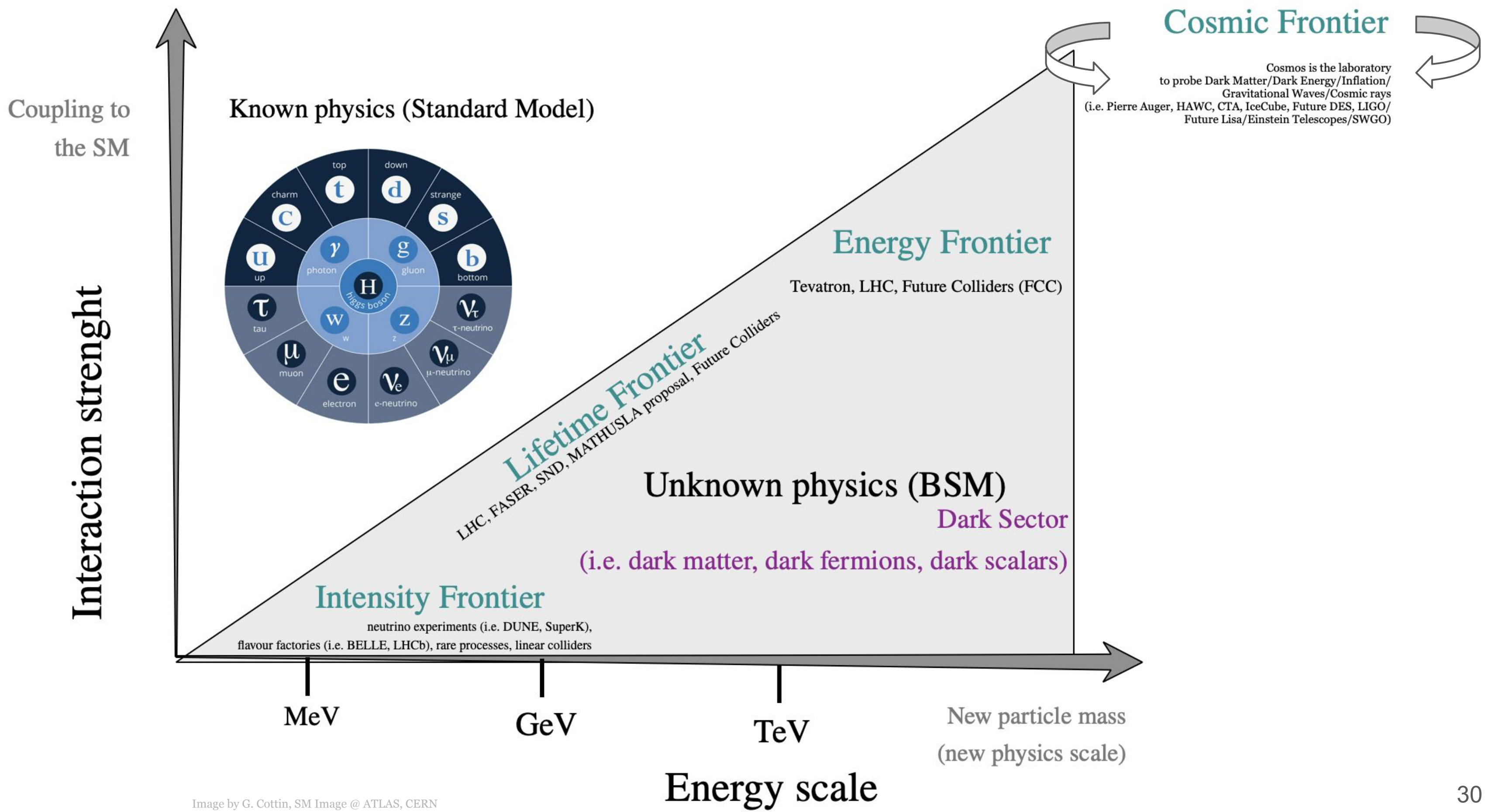


Image by G. Cottin, SM Image @ ATLAS, CERN

A long-lived paradigm shift

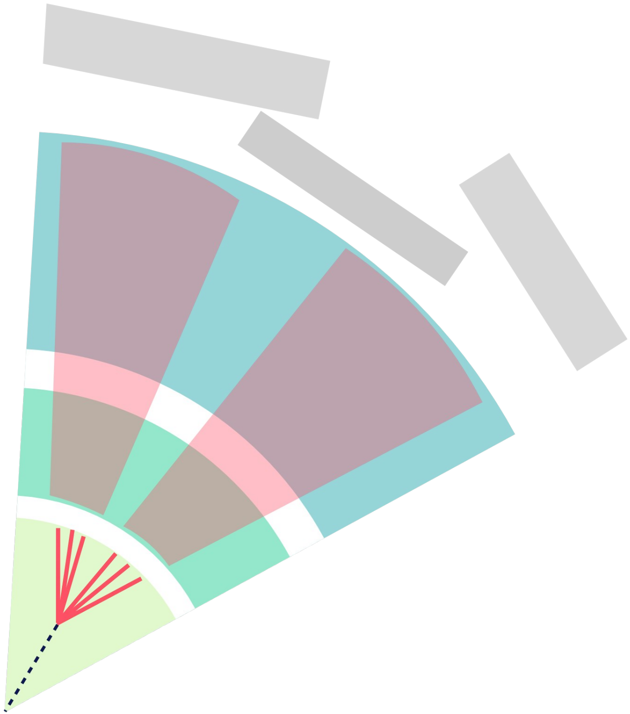


Image from Heather Russel

Backup

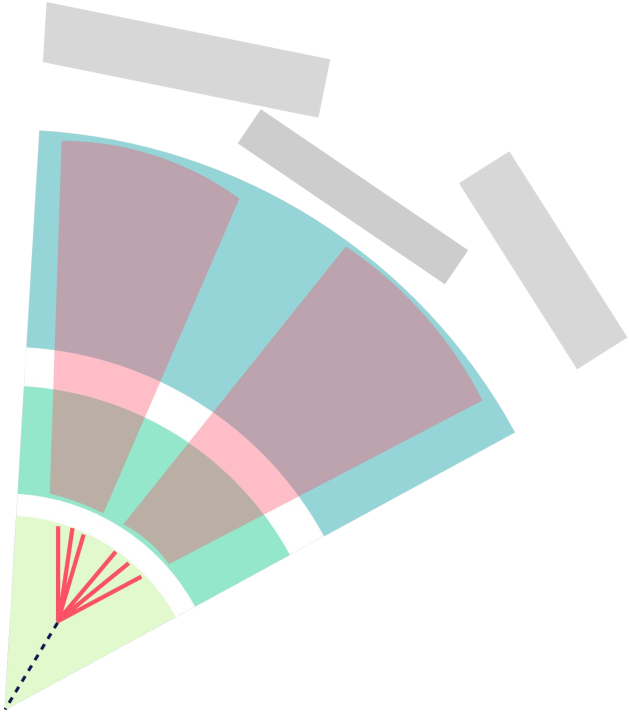
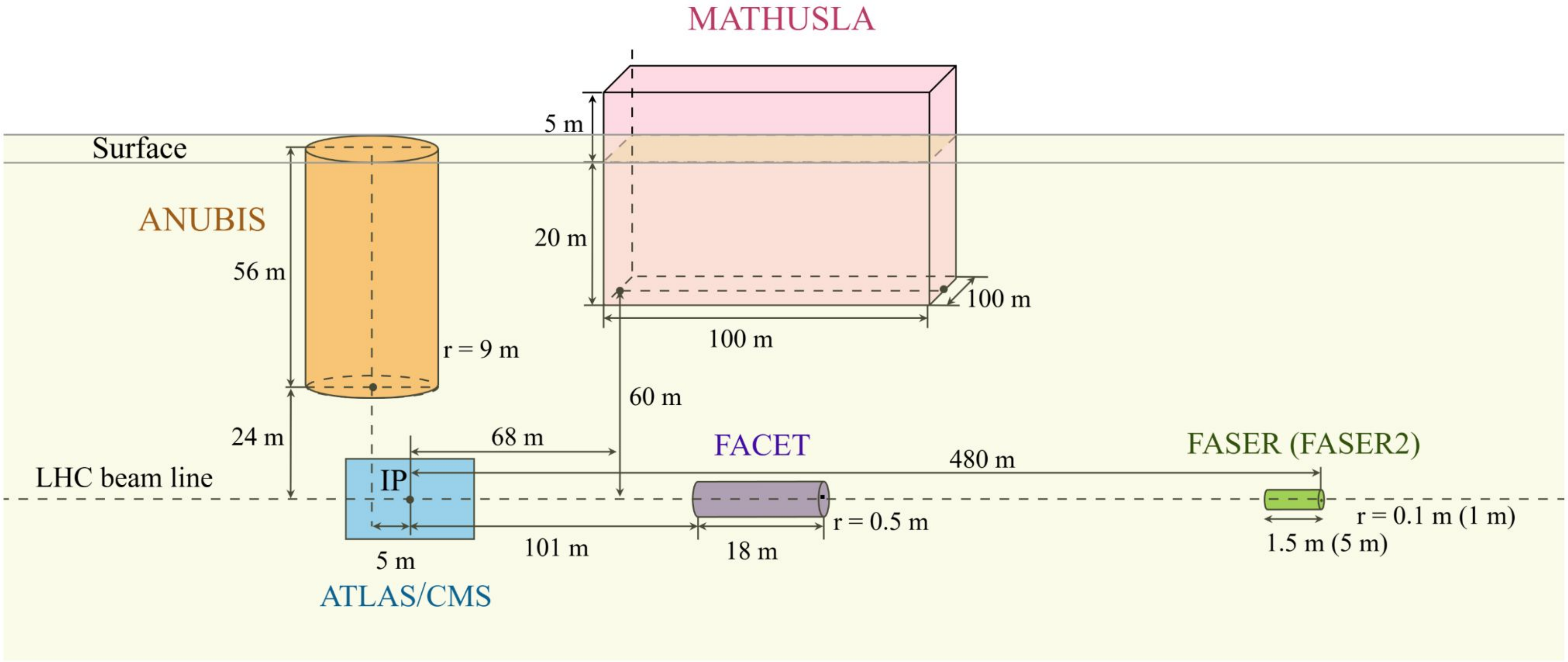


Image from Heather Russel

New approved/proposed transverse far detector experiments complement reach

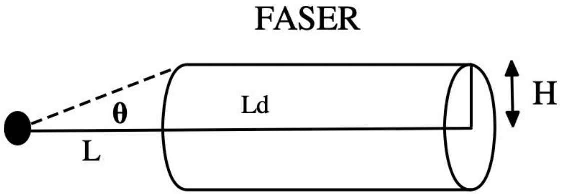


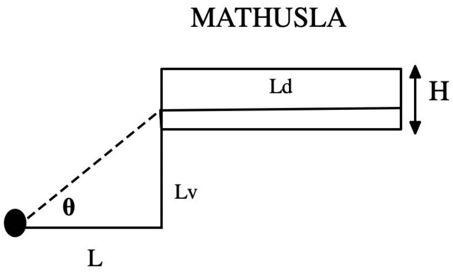
Details of probability of decay formulas in fiducial volumes
See A C++ program for estimating detector sensitivities to long-lived particles, F. Domingo, J. Günther, J. S. Kim, Z.S. Wang, Eur.Phys.J.C 84 (2024), arXiv:2308.07371
Jordy de Vries, H. K. Dreiner, J. Y. Günther, Z. S. Wang, G. Zhou, 2010.07305 (JHEP 03 (2021))
For FASER, MATHUSLA and CODEX-b see D. Dercks, J. de Vries, H. K. Dreiner, Z. S. Wang, 1810.03617 (Phys. Rev. D 99, 055039 (2019)) *and earlier in*
J.C. Helo, M. Hirsch, Z. S. Wang, 1803.02212 (JHEP 07 (2018))
For ANUBIS see M. Hirsch, Z. S. Wang, 2001.04750 (Phys. Rev. D 101, 055034 (2020))
For AL3X see D. Dercks, H.K. Dreiner, M. Hirsch, Z. S. Wang,1811.01995 (Phys.Rev. D 99, 055020 (2019))
For MAPP see H. K. Dreiner, J. Y. Günther, Z. S. Wang, 2008.07539 (Phys. Rev. D 103, 075013 (2021))

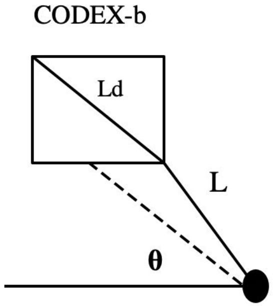
Diagram from C.-T. Lu, X. Wang, X. Wei, Y. Wu, arXiv:2410.19561

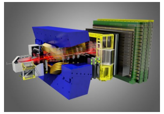
Geometry for LLP detectors

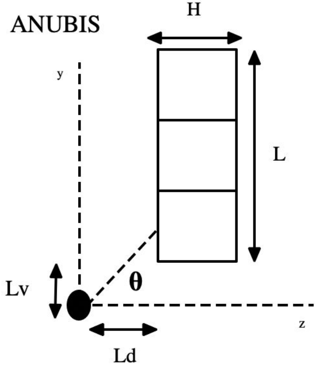
Decay probability of each simulated HNL takes into account the far detector geometry (L, Ld, Lv, H, θ) and their kinematics

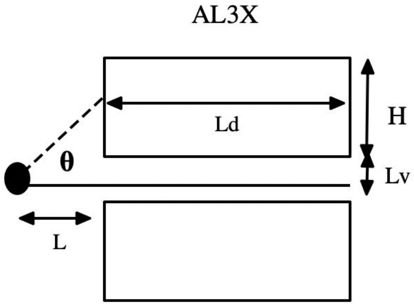


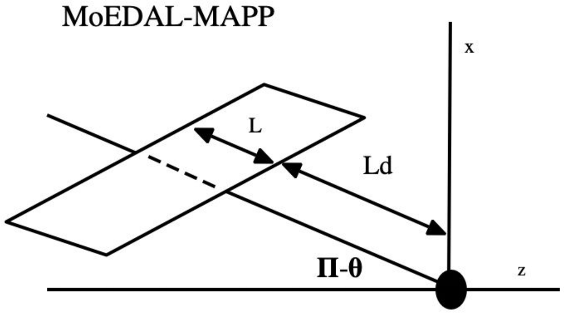












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For ANUBIS see M. Hirsch, Z. S. Wang, 2001.04750 (Phys. Rev. D 101, 055034 (2020))
For AL3X see D. Dercks, H.K. Dreiner, M. Hirsch, Z. S. Wang,1811.01995 (Phys.Rev. D 99, 055020 (2019))
For MAPP see H. K. Dreiner, J. Y. Günther, Z. S. Wang, 2008.07539 (Phys. Rev. D 103, 075013 (2021))

LLP far detectors

FASER

Cylinder with $r = 10$ cm and $\ell = 1.5$ m

$c\tau \sim 480$ m

Boosted cross section

$4\pi/10^3$ coverage

CoDEX-b

Box of $10\,\text{m} \times 10\,\text{m} \times 10\,\text{m}$

$c\tau \sim 25$ m

$4\pi/10^2$ coverage

Lower luminosity

ANUBIS

Cylinder with $r = 9$ m and $h = 56$ m

$c\tau \sim$ few 10 m

$4\pi/50$ coverage

MATHUSLA

Box of $100\,\text{m} \times 100\,\text{m} \times 25\,\text{m}$

$c\tau \sim \mathcal{O}(100\,\text{m})$

$4\pi/25$ coverage

AL3X: A Laboratory for Long-Lived eXotics

@ALICE

Cylinder with 0.85 m $< r < 5$ m and $\ell = 12$ m

$c\tau \sim 10$ m

MoEDAL-MAPP: MoEDAL's Apparatus for Penetrating Particles

(MoEDAL: Monopole and Exotics Detector at the LHC)

@LHCb

MAPP1: ~ 130 m^3

MAPP2: ~ 430 m^3

$c\tau \sim 50$ m

With thanks to A. Titov

“HNL optimized” displaced strategies/proposals in the Minimal HNL Model that build up on experimental LLP searches not necessarily designed for HNLs (apologies if I missed your work!)

Displaced vertex searches

- HNL decays leptonically and/or semileptonically
- prompt lepton trigger from W decay at LHC

Inner Trackers (IT)

- high-mass and displaced track multiplicity DVs in inner tracker to suppress hadronic bkgs.

J. C. Helo, M. Hirsch, S. Kovalenko, PRD 89 (2014), G. Cottin, J.C. Helo and M. Hirsch, PRD 98 (2018), Iryna Boiarska et al., arXiv:1902.04535, A. Abada, N. Bernal, M. Losada and X. Marcano JHEP 93 (2019), M. Drewes, J. Hajer, JHEP 70 (2020)

Muon Systems (MS)

- can access larger displacements (i.e lower HNL masses)
- purely muonic vertices give better sensitivity at low HNL masses (not necessarily limited by invariant mass cut of DV)

K. Bondarenko et al.,Phys. Rev. D 100 (2019)
M. Drewes, J. Hajer, JHEP 70 (2020)

Future colliders

- can access lower mixings due to large elec-pos production at the Z pole

S. Antusch, O. Fischer, A. Hammad, JHEP 03 (2020)
J. Alimena, et. al, Front. Phys. 10:967881 (2022)
S Ajmal, et al.,arXiv:2410.03615

Displaced lepton searches

- HNL decays leptonically
- prompt lepton trigger
- At least one displaced track from HNL is a non-isolated lepton
- Can do explicit vertex reconstruction of displaced di-muon/di-electron/emu vertices in ID or MS
- No explicit vertex requirement leads to additional sources of SM bkgs.

J. Liu, Z. Liu, Lian-Tao Wang, Xiao-Ping Wang, JHEP 07(2019)
M. Drewes, J. Hajer, JHEP 70 (2020)
LHC HNL displaced searches for displaced dilepton DV: ATLAS 1905.09787, 2204.11988, CMS 2201.05578, LHCb 2011.05263

Displaced lepton-jets

- Prompt lepton trigger from W decay
- Reconstruct boosted HNL decay as a single displaced *lj* object (with more than one leptonic displaced track concentrated within a cone)

E. Izaguirre and B. Shuve, Phys. Rev. D91 (2015)
S. Dube, D. Gadkari, and A. M. Thalapillil, Phys. Rev. D96 (2017)

Displaced shower

- MET/displaced triggers
- Reconstruction of cluster of hits @CMS

G.Cottin, J.C. Helo, M. Hirsch, C. Peña, C. Wang, S. Xie , JHEP02(2023)011
CMS PAS-EXO-22-017

SST Model

Fields	$SU(3)_C$	$SU(2)_L$	$U(1)_Y$	$\mathbb{Z}_2$
(Real) S_1	1	1	0	$-$
S_3	1	3	1	$-$
F $(\overline{F})$	1	2	$1/2$ $(-1/2)$	$-$

Table 1. Quantum numbers for the particle content of the model. While neutrino masses could be explained already with one copy of $F/\overline{F}$, in our numerical study we use three families of $F/\bar{F}$ to reflect the number of generations in the SM.

The triplet scalar can be written in the usual way:

$$S_3 = \begin{pmatrix} t^+/\sqrt{2} & t^{++} \\ t^0 & -t^+/\sqrt{2} \end{pmatrix}. \tag{2.1}$$

The Lagrangian of the model adds the following terms to the SM Lagrangian:

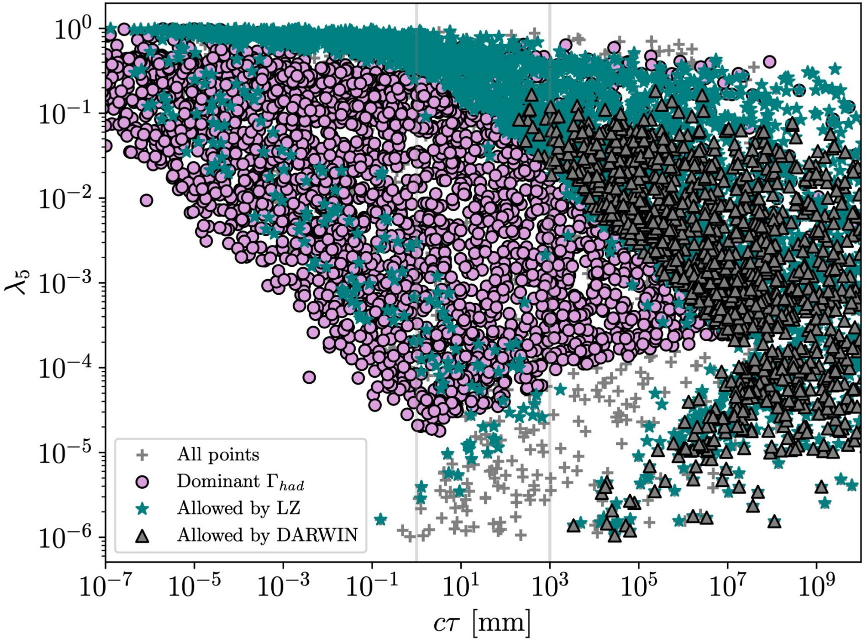
$$\begin{aligned} \mathcal{L} = &-(M_F F\bar{F} + M_{S_1}^2|S_1|^2 + M_{S_3}^2|S_3|^2) - (h_F LFS_1 + h_{\bar{F}}L\bar{F}S_3 + \text{h.c.}) \\ &+ \lambda_2|H|^2|S_1|^2 + \left(\lambda_{3a}|H|^2|S_3|^2 + \lambda_{3b}\epsilon_{l_1 l_3}\epsilon_{l_2 l_4}\epsilon_{l_{3b} l_{4_b}} H_{l_1} H^*_{l_2}(S_3)_{l_3 l_{3b}}(S_3^*)_{l_4 l_{4b}}\right) \\ &+ \lambda_4(|S_1|)^4 - (\lambda_5 HHS_1S_3^\dagger + \text{h.c}) \end{aligned} \tag{2.2}$$

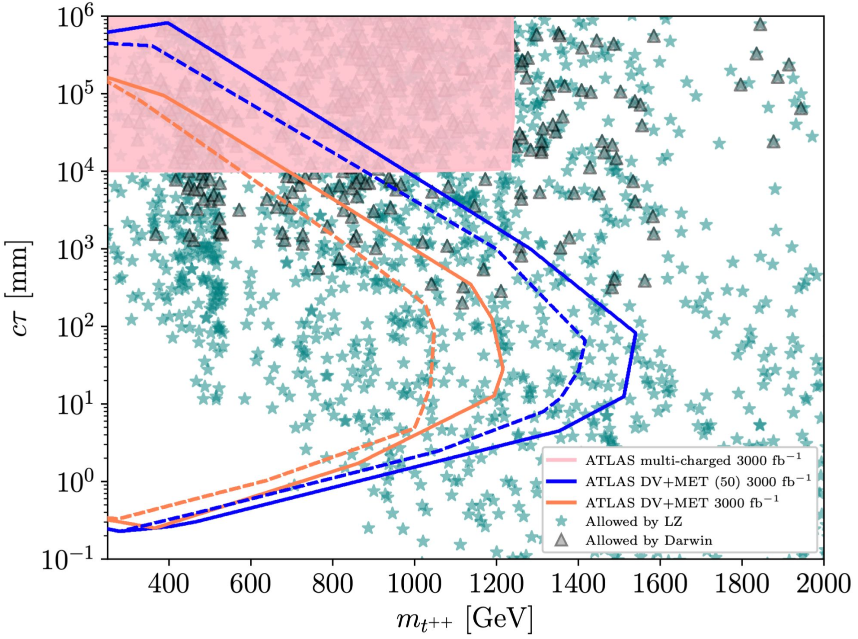
SST Model

$$(m_{s_1^0,s_2^0})^2 = \frac{1}{4}\Big(2(M_{S_1}^2 + M_{S_3}^2) - (\lambda_2 + \lambda_{3_a})v^2 \mp \sqrt{\left(2(M_{S_1}^2 - M_{S_3}^2) + v^2(\lambda_{3_a} - \lambda_2)\right)^2 + 8\lambda_5^2 v^4}\Big),$$

$$m_{t^{++}}^2 = M_{S_3}^2 - \frac{1}{2}\left(\lambda_{3a} + \lambda_{3b}\right) v^2,$$

$$m_{t^{+}}^2 = M_{S_3}^2 - \frac{1}{4}\left(2\lambda_{3a} + \lambda_{3b}\right) v^2.$$


All points
Dominant Γ_{had}
Allowed by LZ
Allowed by DARWIN
λ_5
$c\tau$ [mm]


ATLAS multi-charged 3000 fb^{-1}
ATLAS DV+MET (50) 3000 fb^{-1}
ATLAS DV+MET 3000 fb^{-1}
Allowed by LZ
Allowed by Darwin
$c\tau$ [mm]
$m_{t^{++}}$ [GeV]