With support from Fondecyt 11220237, 1201673 and ANID – Millennium Science Initiative Program ICN2019_044

Long-lived particle phenomenology

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SAPHIR Millennium Institute, Chile

Based on collaborative work with
R.Beltrán, J.C. Helo, M. Hirsch, A. Titov, Z.S. Wang (2110.15096, 2105.13851)
J.C. Helo, M. Hirsch, C. Peña, C. Wang, S. Xie (2210.17446)
J.C. Helo, F. Hernández, N. Neill, Z.S. Wang (2208.12818)

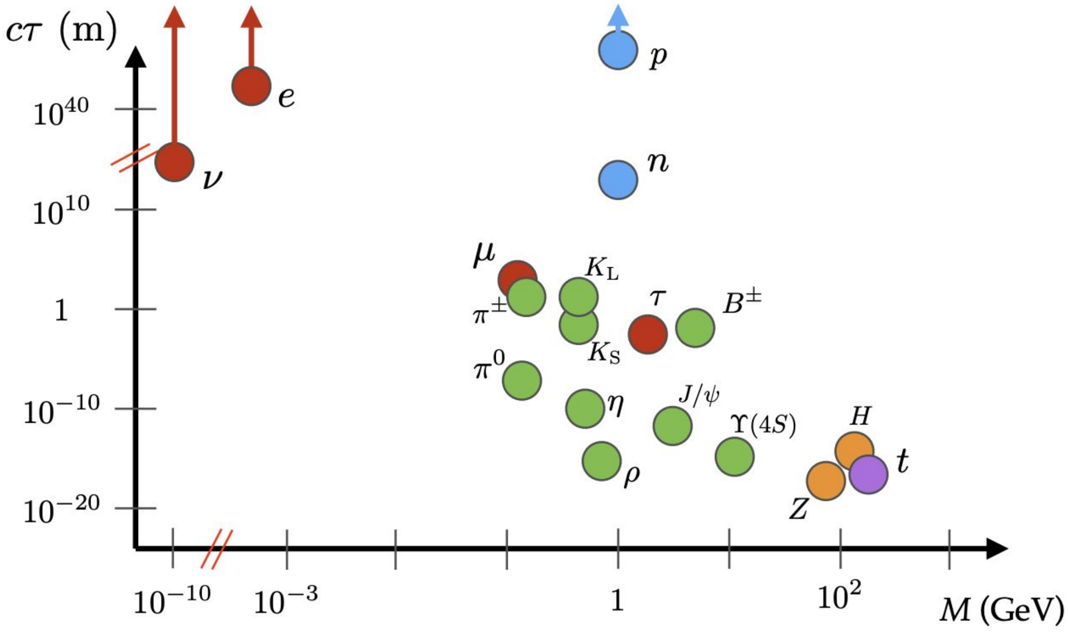
SAPHIR ARM, La Serena, Chile, January 2023

Outline

- Why Long-lived particles beyond the Standard Model?
- Examples of BSM LLP phenomenology at the LHC
- Take home message

LLP Image adapted from Heather Russel

Long-Lived Particles can travel macroscopic distances before decaying inside a particle detector. Our world is full of them



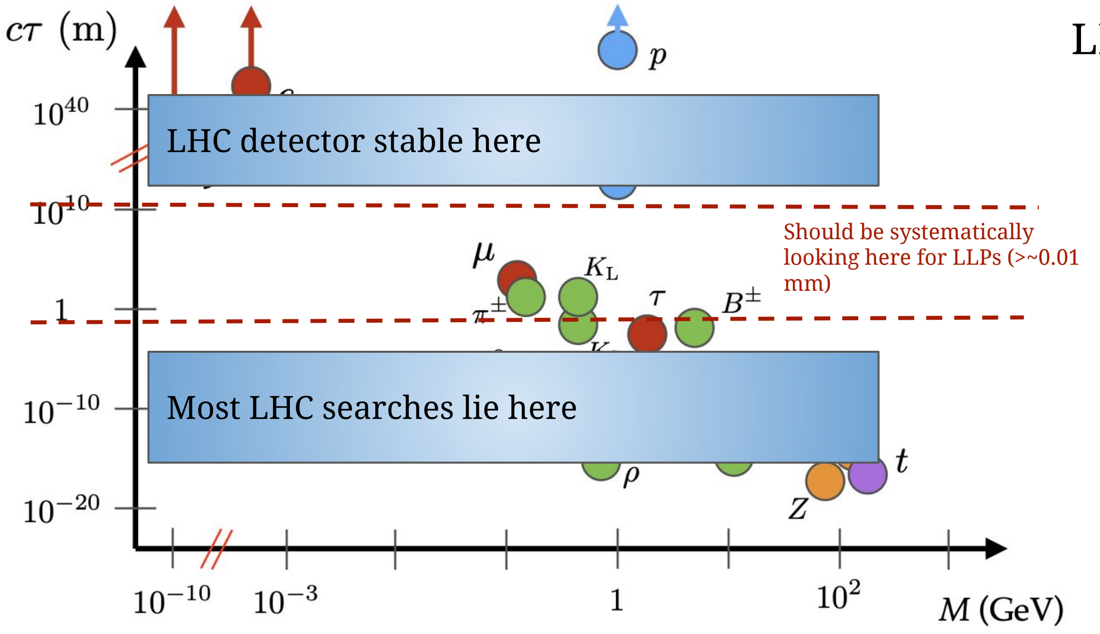
LLPs occur when decay suppressed

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

$$c\tau \sim \Gamma^{-1}$$

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

Long-Lived Particles can travel macroscopic distances before decaying inside a particle detector. Our world is full of them



LLPs occur when decay suppressed

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

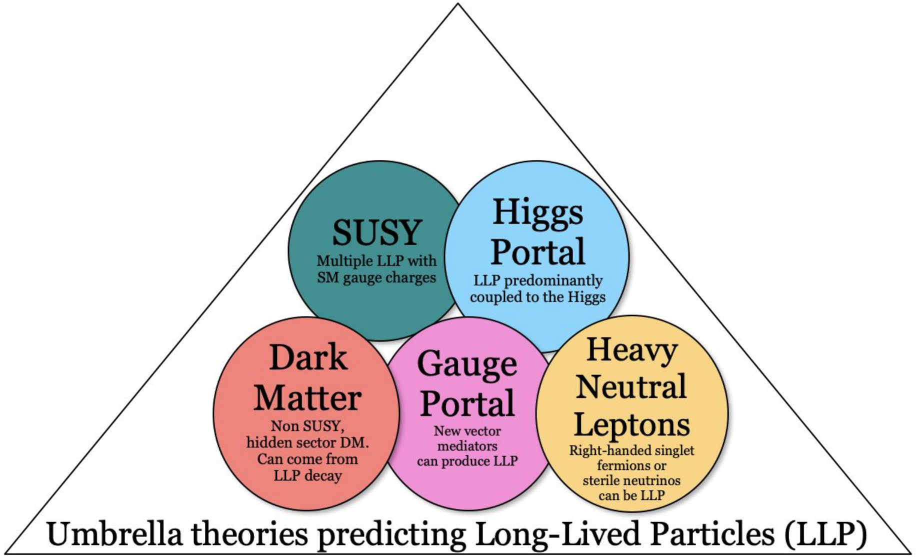
$$c\tau \sim \Gamma^{-1}$$

This can also happen in several beyond the Standard Model theories !

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

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

BSM is needed to understand our world. The Standard Model can not explain it all



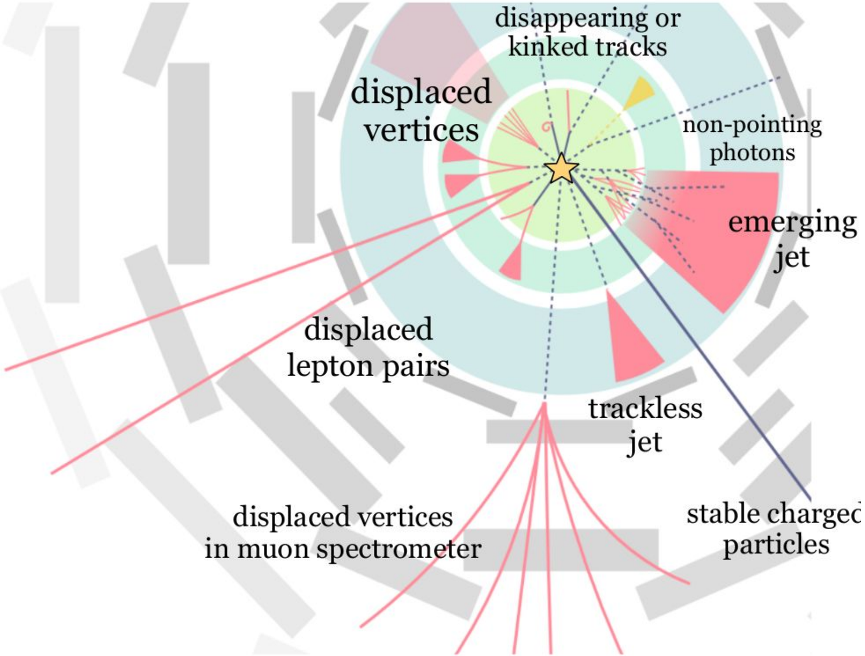
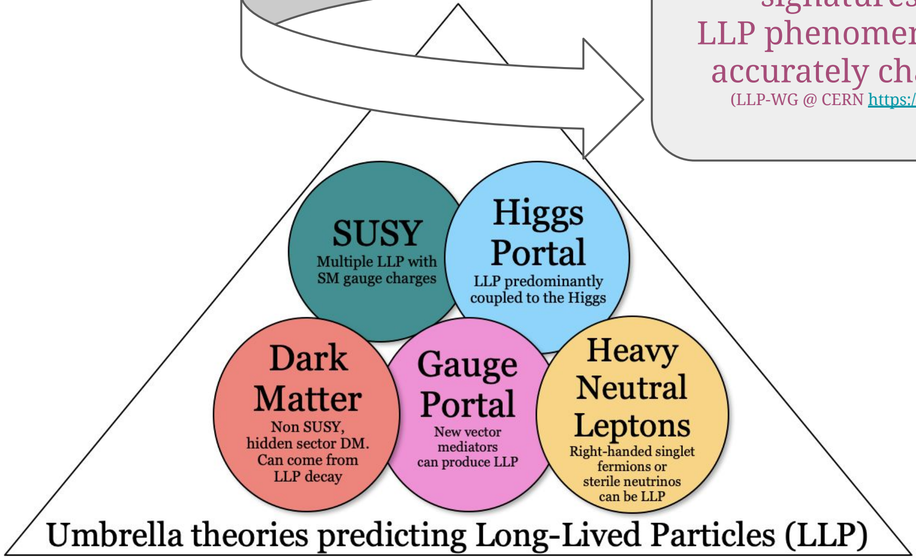


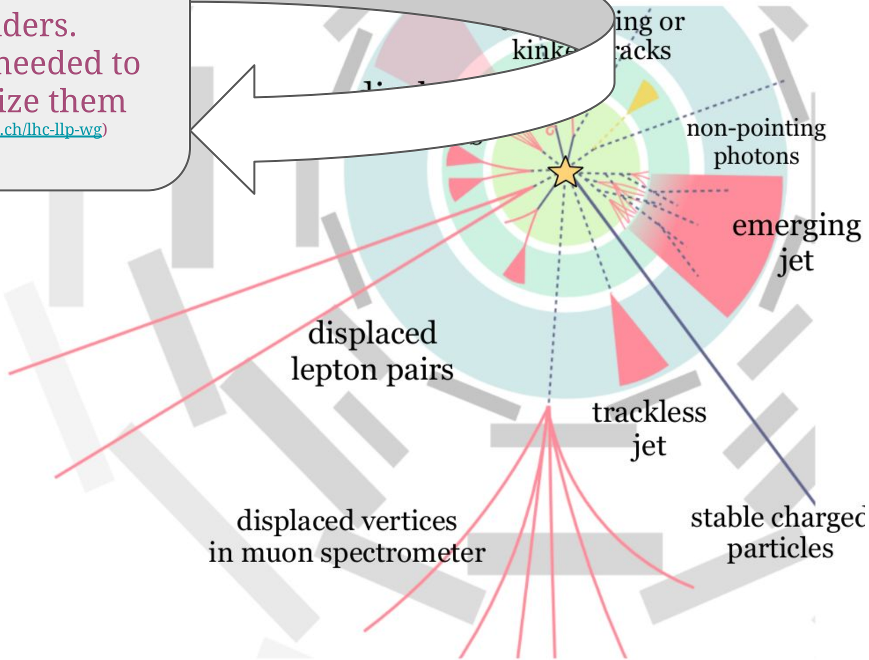
Image by G.Cottin
See simplified models classification in LLP Community White Paper
J. Alimena, .. , G. Cottin, et al, [arXiv:1903.04497]

LLP Image adapted from Heather Russel

BSM is needed to understand our world. The Standard Model can not explain it all

Predictions will yield exotic signatures at colliders.
LLP phenomenology needed to accurately characterize them
(LLP-WG @ CERN https://lpcc.web.cern.ch/lhc-llp-wg)





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Why so complex LLP phenomenology?

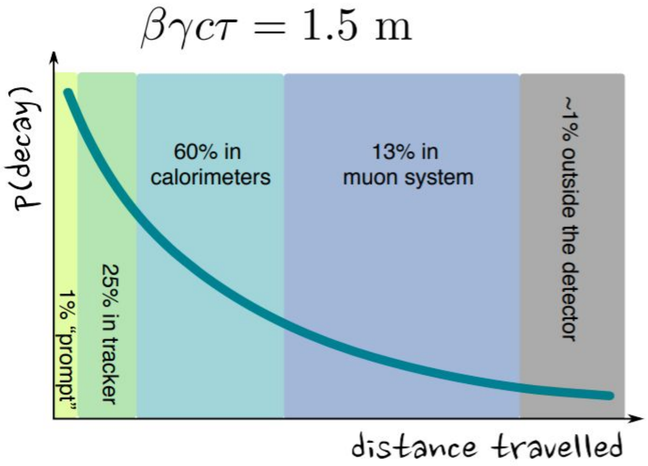
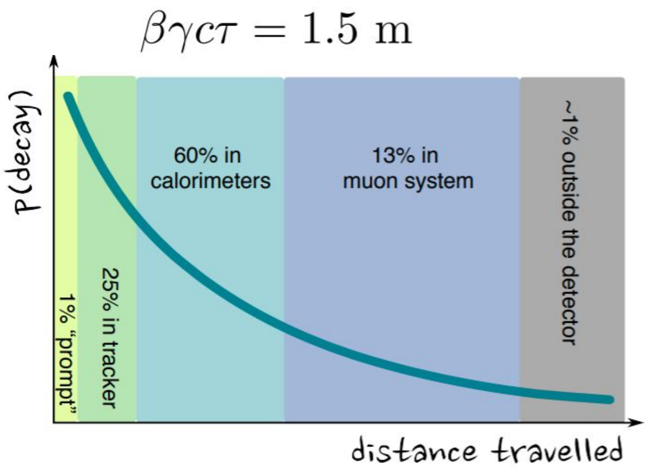


Image by Heather Russel (based on ATLAS geometry)
Long-lived Particle Community Workshop, 2017

For LLPs with with even longer lifetimes will need very different search strategies …

Why so complex LLP phenomenology?



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Long-lived Particle Community Workshop, 2017

For LLPs with with even longer lifetimes will need very different search strategies …

May even need to consider new LLP detectors!

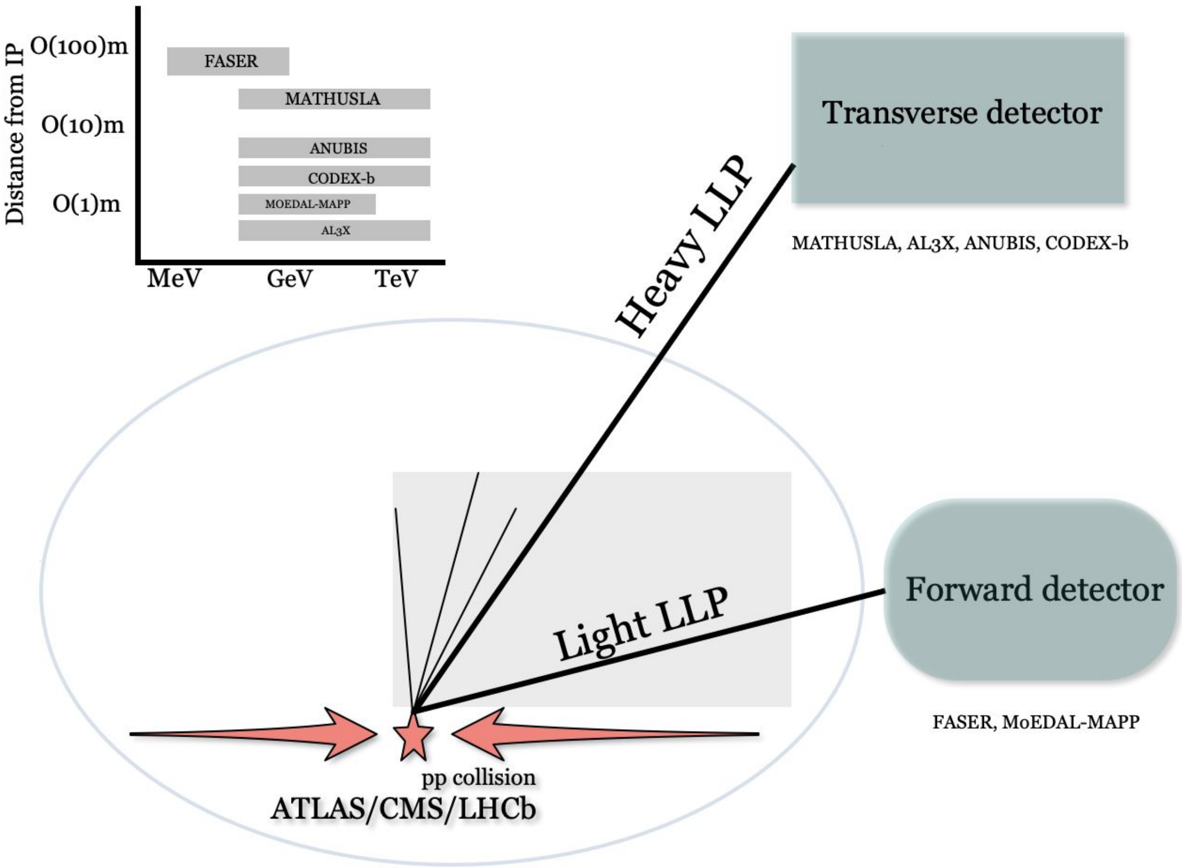
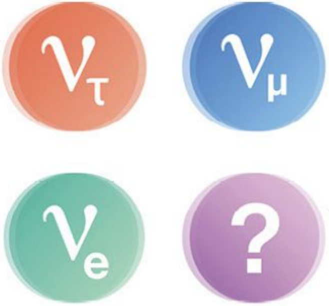


Image by G. Cottin inspired by M.Citron's talk at LLPXII

- Examples of BSM LLP phenomenology at the LHC
  - Heavy Neutral Leptons (HNLs) as LLP (minimal case and SMEFT+HNLs)
  - Light neutralino as LLP within R-Parity Violating SUSY

LLP Image adapted from Heather Russel



https://neutrinos.fnal.gov/whats-a-neutrino/

LLP Motivation: An answer for neutrino mass generation mechanism. See Jose Valle’s and M. Hirsch’s talks!

(For a dark matter motivation, see M.A.Díaz’s talk!)

- Examples of BSM LLP phenomenology at the LHC
  - Heavy Neutral Leptons (HNLs) as LLP (minimal case and SMEFT+HNLs)
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LLP Image adapted from Heather Russel

Seesaw Mechanism(s)

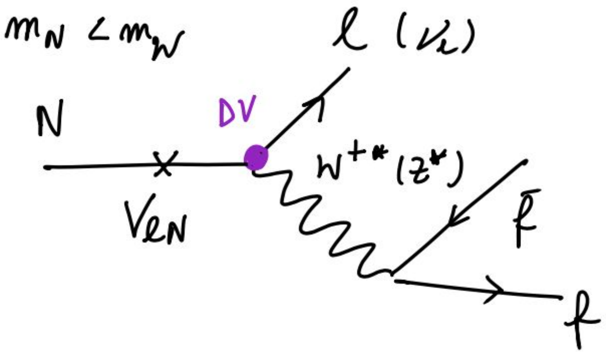
- Predicts HNLs
- HNLs mix with SM neutrinos
- Can be realised in many BSM models

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)

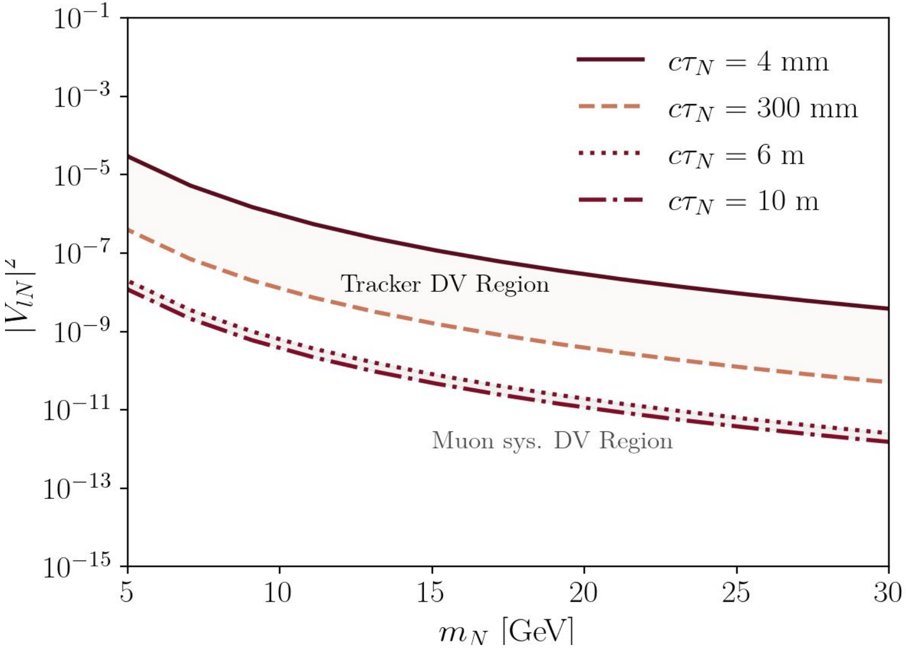
Inverse seesaw
R. Mohapatra and J. Valle, Phys. Rev. D34 (1986) 1642

$$\Gamma \sim G_F^2 |V_{\ell N}|^2 m_N^5$$

Small mixings and ~GeV scale HNL yields macroscopic lifetime



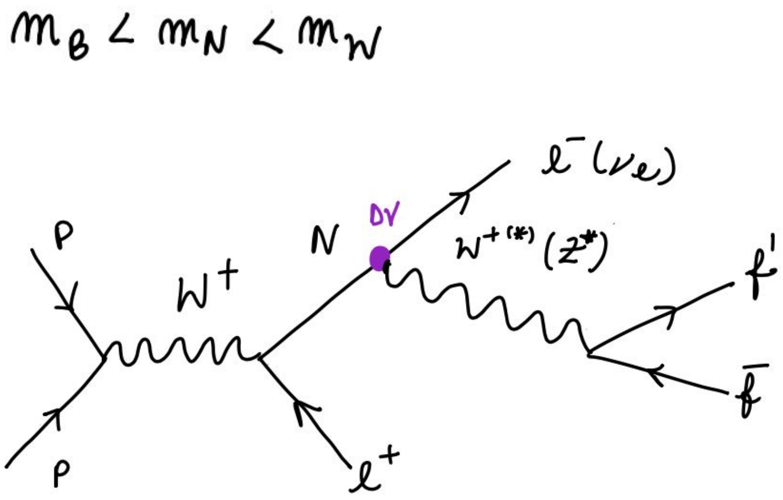
Adapted from G. Cottin, J.C. Helo and M. Hirsch, PRD 98 (2018)

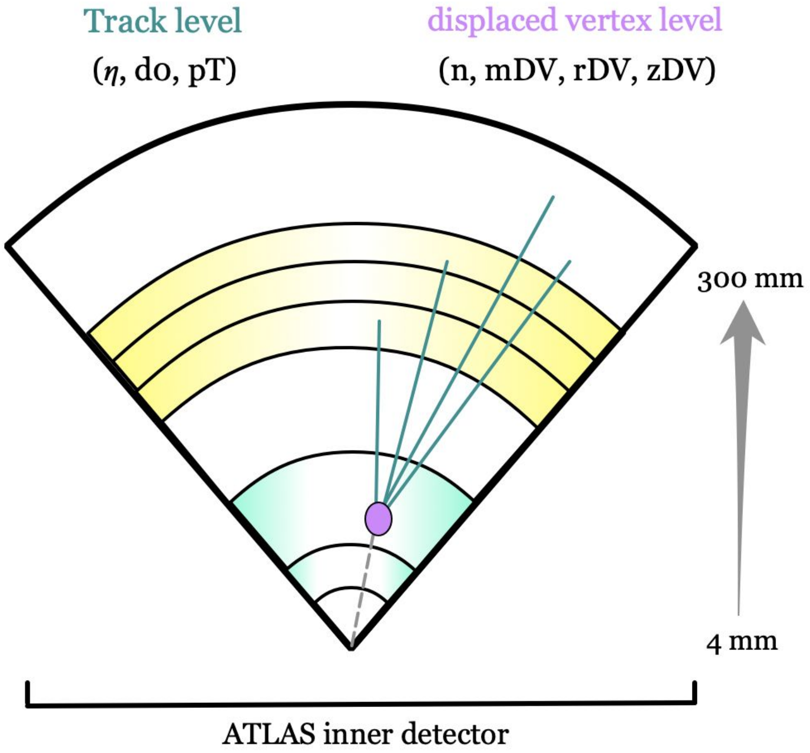


Catching HNLs with inner tracker displaced vertices

“HNL optimized” multitrack DV search strategy

First proposed in G. Cottin, J.C. Helo and M. Hirsch, PRD 98 (2018)
Builds up on ATLAS SUSY searches in 1710.04901, 1504.05162
Updated in R. Beltrán, G. Cottin, J.C. Helo, M. Hirsch, A. Titov, Z.S. Wang, 2110.15096



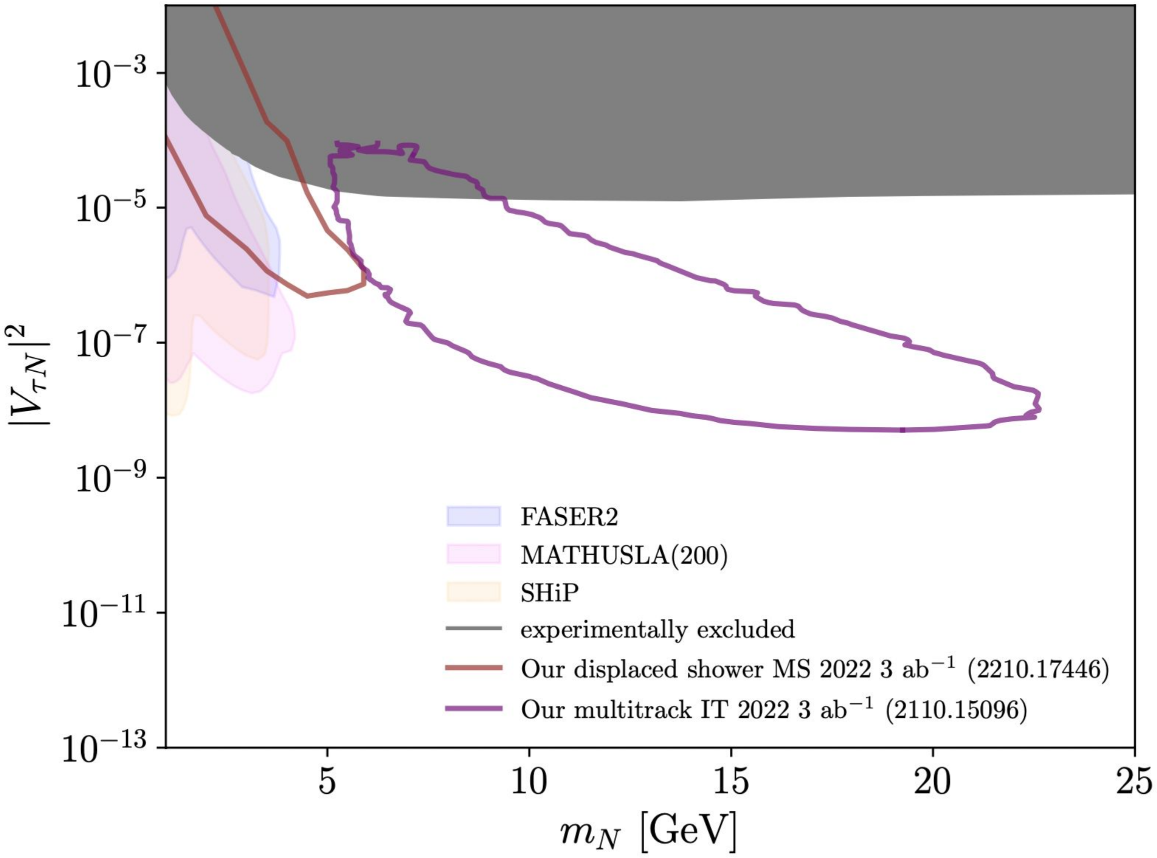


For other proposals and mass regions at different lifetime frontier experiments see *The Present and Future Status of Heavy Neutral Leptons*, Snowmass, arXiv: 2203.08039

Image by G. Cottin

Tau-mixing not covered yet at LHC, what can we do? Propose new searches with current LHC detector subsystems !

R. Beltrán, G. Cottin, J.C. Helo, M. Hirsch, A. Titov, Z.S. Wang, 2110.15096, JHEP 01 (2022) 044
G.Cottin, J.C. Helo, M. Hirsch, C. Peña, C. Wang, S. Xie (2210.17446), JHEP accepted last week !



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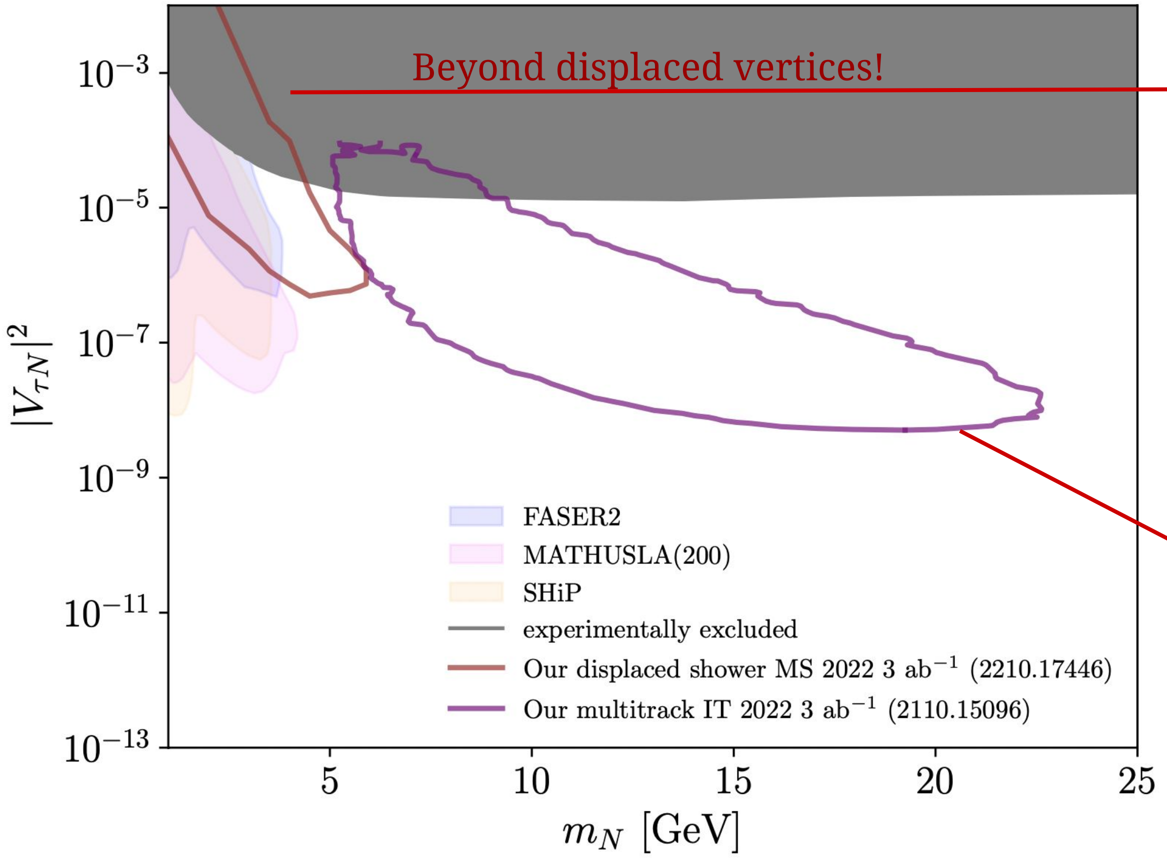
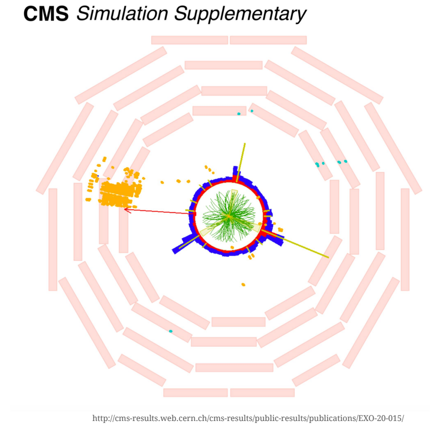
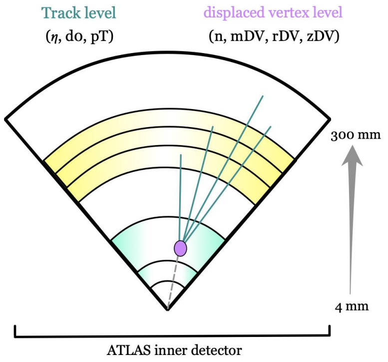






Not all the parameter space of all BSM models predicting HNLs is covered at the LHC, what can we do? Go to NRSMEFT to systematically study them !

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

d=6 four-fermion operators with *a single* HNL

R. Beltrán, G. Cottin, J.C. Helo, M. Hirsch, A. Titov, Z.S. Wang, 2110.15096 (JHEP 01 (2022) 044)

Name	Structure (+ h.c.)	$n_N = 1$	$n_N = 3$
$\mathcal{O}_{duNe}$	$(\overline{d_R}\gamma^\mu u_R)(\overline{N_R}\gamma_\mu e_R)$	54	162
$\mathcal{O}_{LNQd}$	$(\overline{L}N_R)\epsilon(\overline{Q}d_R)$	54	162
$\mathcal{O}_{LdQN}$	$(\overline{L}d_R)\epsilon(\overline{Q}N_R)$	54	162
$\mathcal{O}_{LNLe}$	$(\overline{L}N_R)\epsilon(\overline{L}e_R)$	54	162
$\mathcal{O}_{QuNL}$	$(\overline{Q}u_R)(\overline{N_R}L)$	54	162

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

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

G. Cottin, J. C. Helo, M. Hirsch, A. Titov, Z. S. Wang, 2105.13851, (JHEP 09 (2021) 039)

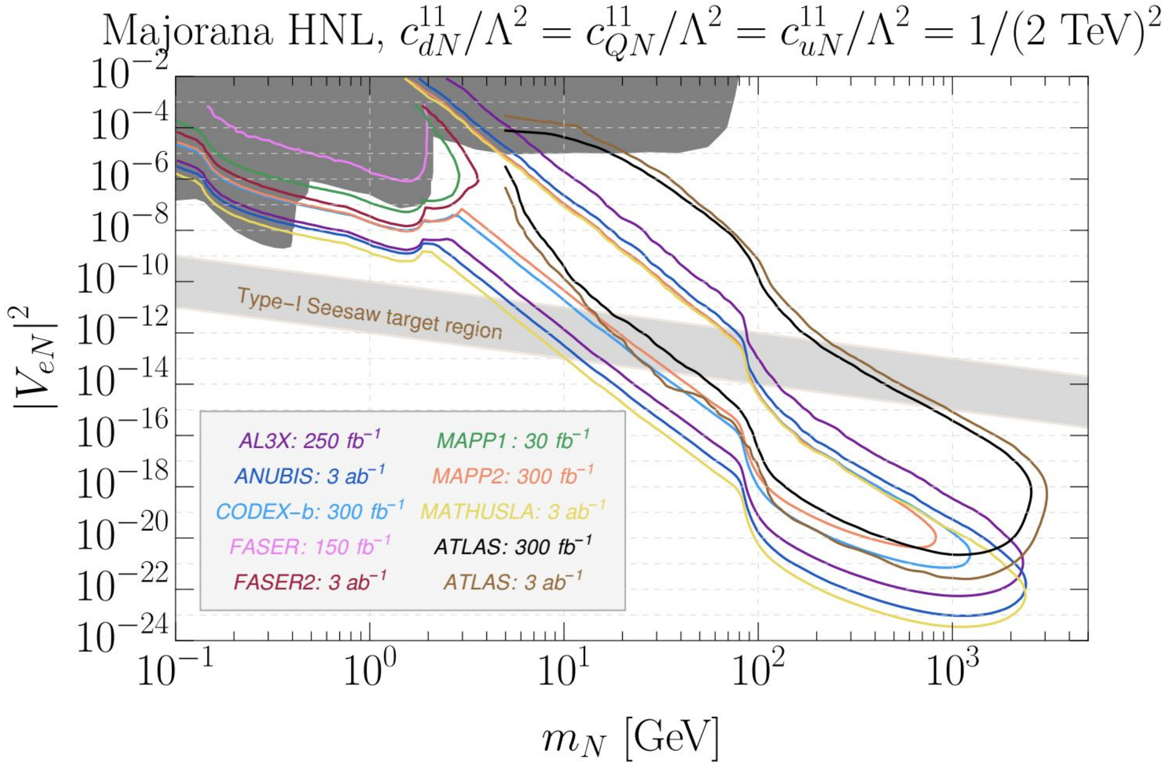
Name	Structure	$n_N = 1$	$n_N = 3$
$\mathcal{O}_{dN}$	$(\overline{d_R}\gamma^\mu d_R)(\overline{N_R}\gamma_\mu N_R)$	9	81
$\mathcal{O}_{uN}$	$(\overline{u_R}\gamma^\mu u_R)(\overline{N_R}\gamma_\mu N_R)$	9	81
$\mathcal{O}_{QN}$	$(\overline{Q}\gamma^\mu Q)(\overline{N_R}\gamma_\mu N_R)$	9	81
$\mathcal{O}_{eN}$	$(\overline{e_R}\gamma^\mu e_R)(\overline{N_R}\gamma_\mu N_R)$	9	81
$\mathcal{O}_{NN}$	$(\overline{N_R}\gamma_\mu N_R)(\overline{N_R}\gamma_\mu N_R)$	1	36
$\mathcal{O}_{LN}$	$(\overline{L}\gamma^\mu L)(\overline{N_R}\gamma_\mu N_R)$	9	81

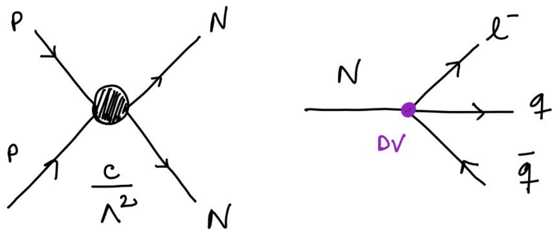
Additional HNLs in EFT with LLPs at the LHC studies
d=5 in A. Caputo, P. Hernandez, J. Lopez-Pavon, J. Salvado, JHEP 06 (2017)
Jordy de Vries, H. K. Dreiner, J. Y. Günther, Z. S. Wang, G. Zhou, JHEP 03 (2021)
R.Beltrán, G. Cottin, J.C. Helo, M. Hirsch, A. Titov, Z.S. Wang, JHEP 01 (2023)

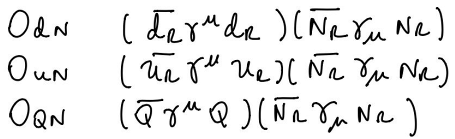
Sensitivities estimates at ATLAS and future LLP detectors

An example for *d=6* four-fermion operators with *pairs* of HNL

G. Cottin, J. C. Helo, M. Hirsch, A. Titov, Z. S. Wang, 2105.13851, (JHEP 09 (2021) 039)







Much larger sensitivities can be achieved as compared to the minimal HNL scenario !

SUSY
Multiple LLPs with SM gauge charges

Long-lived neutralino in SUSY RPV

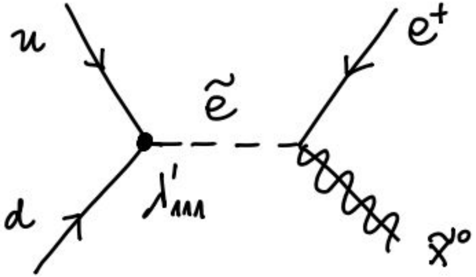
SUSY RPV
R. Barbier et al, Phys.Rept. 420 (2005)
H. K. Dreiner, G. G. Ross, Nucl. Phys. B365 (1991)

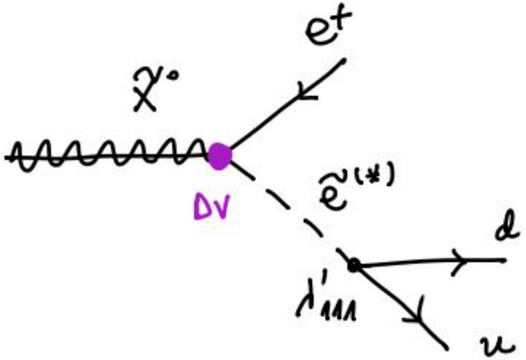
Seminal Displaced SUSY RPV
P. W. Graham, D. E. Kaplan, S. Rajendran, P. Saraswat, JHEP 1207 (2012) 149, arXiv:1204.6038

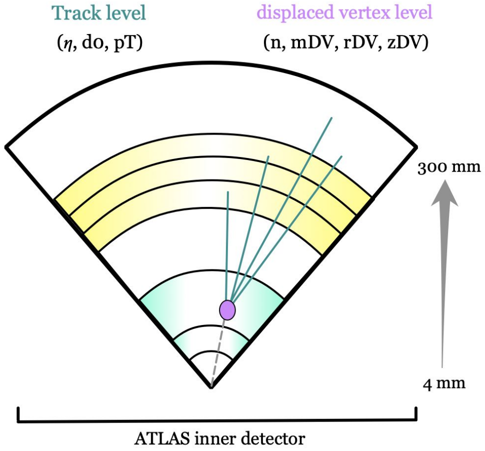
$$W_{RPV} = \lambda'_{ijk} \hat{L}_i \hat{Q}_j \hat{D}_k$$

$$\Gamma \sim \lambda'^2_{111} \, m_{\tilde{f}}^{-4} \, m_N^5$$

Small couplings and light neutralino give rise to macroscopic neutralino lifetime



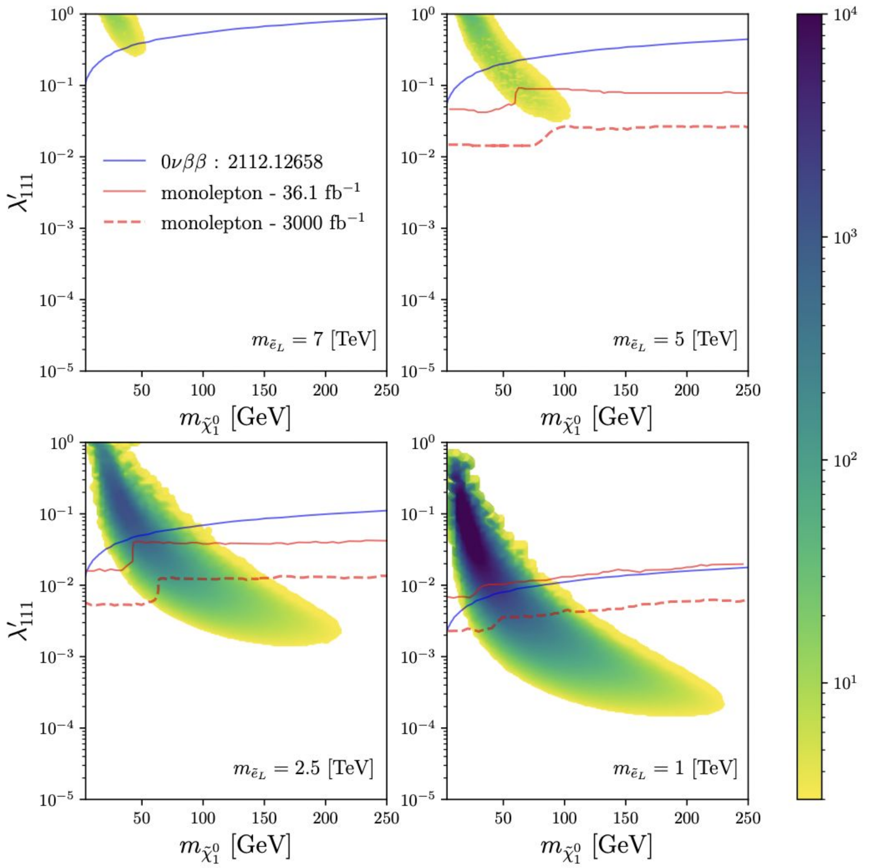




- The process gives rise to a displaced vertex signature in the ATLAS inner tracker

Light neutralino sensitivity with displaced vertices

G. Cottin, J. C. Helo, F. Hernández, N. Neill and Z. S. Wang, *JHEP* 10 (2022) 095, 2208.12818



Reinterpreted bounds from M. Aaboud et al. (ATLAS), Eur. Phys. J. C 78, 401 (2018), arXiv:1706.04786
P. D. Bolton, Frank F. Deppisch, P.S. Bhupal Dev, JHEP 03 (2022) 152, arXiv:2112.12658

Proposal with displaced vertices can probe yet unexplored regions in neutralino mass and lambda '111 coupling !

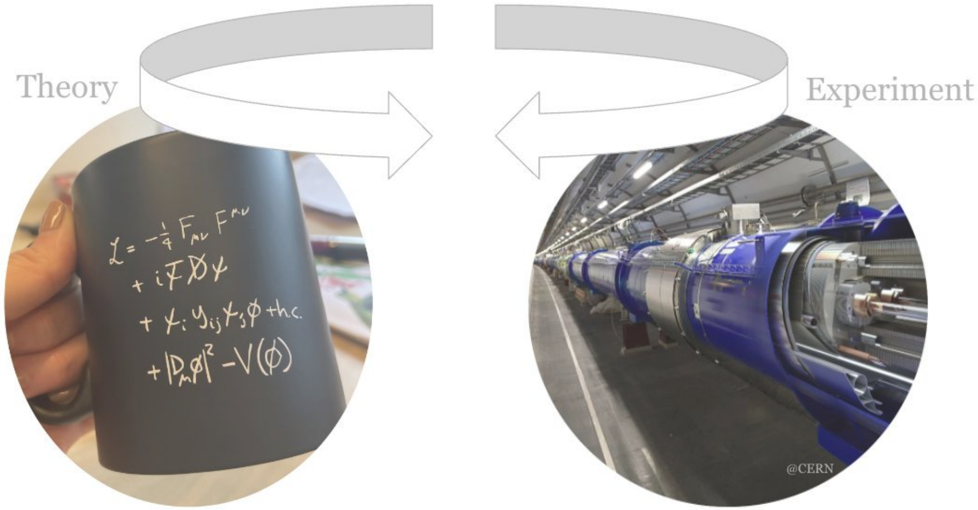
We need BSM. BSM can be long-lived and so it may be hiding at the Large Hadron Collider in exotic/displaced signatures

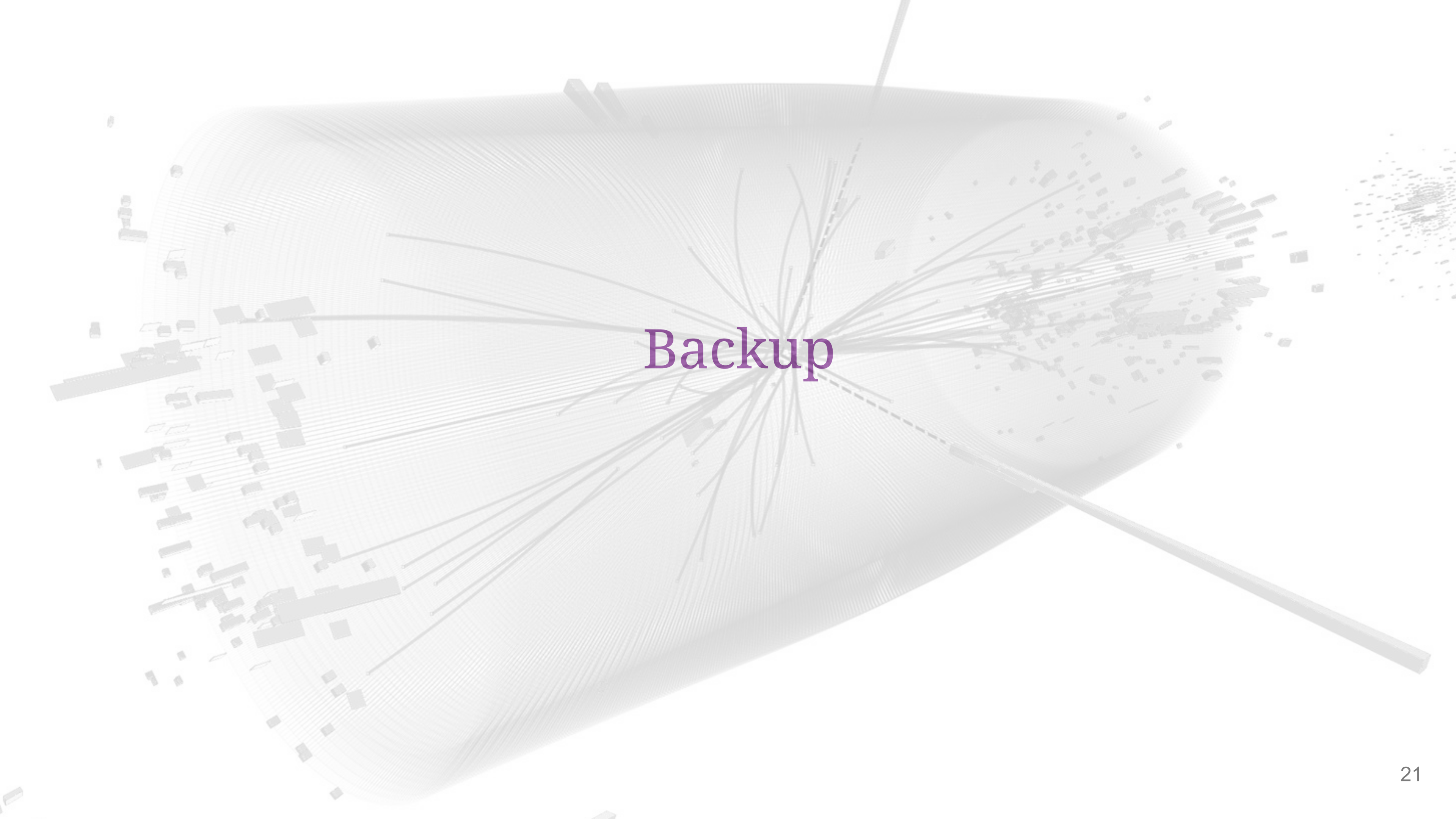
What BSM theories can be tested at current or future experiments and *how*?

We need BSM. BSM can be long-lived and so it may be hiding at the Large Hadron Collider in exotic/displaced signatures

What BSM theories can be tested at current or future experiments and *how*?

This drives the need for reinterpretation and the need to design/propose optimal LLP searches for well motivated theories. LLP phenomenology lies at the cutting edge of LHC physics !





Backup

Theory meets Reality

Many BSM Models predicting LLPs of interest addressing

Neutrino Masses
Dark Matter
Baryogenesis
Naturalness
Anomaly explanations …

Not always being looked for @ experiments

- Lack of person power/time/resources
- Not optimal analysis strategy within experiments
- No standard definition of LLP object(s)
- LLP bkg. hard to simulate outside experiments
- No optimal experiment for your model … or
  Not even an existing detector able to catch your LLP!

There is need for reinterpretation. There is need to propose/design optimal BSM LLP searches

Theorist's roadmap

to reinterpret or propose a new physics search for your model

Characterization of BSM Physics ⟺ Usage/Design ⟺ Evaluate Experimental Response

Characterization of BSM Physics

- Model building
- Identify production modes
- Identify decay patterns
- Hard Code your model (i.e. dedicated software as FeynRules/SARAH/SPHENO)

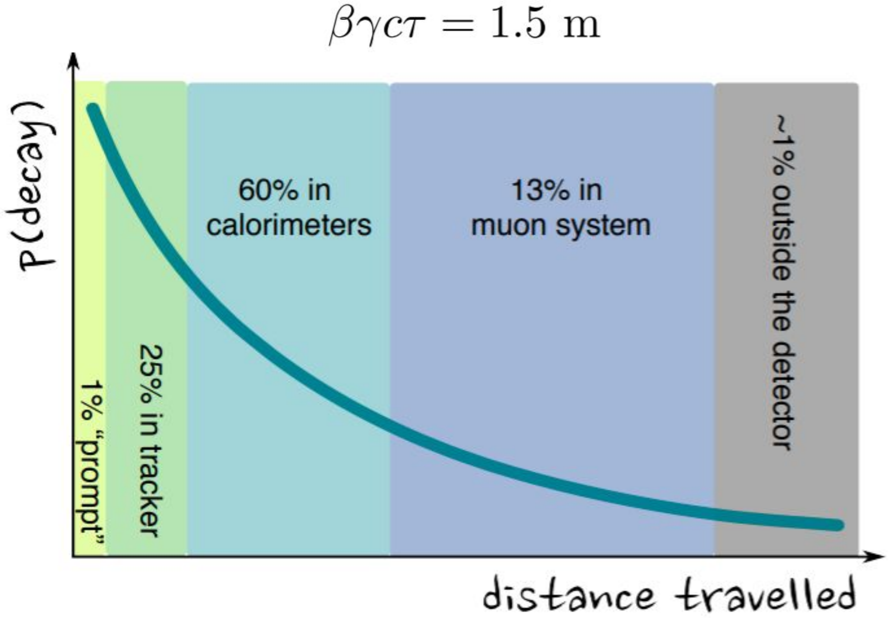
Usage/Design

- Identify Software (i.e. Monte Carlo as Madgraph, Pythia, Herwig ...)
- Design/Implement Observables (i.e. invariant mass, displaced vertex, jets)
- Hard Code your strategy/analysis (i.e. can use standard software as MadAnalysis, Rivet or your own)

Evaluate Experimental Response

- Detector Simulation (i.e. software as DELPHEs or custom made to your analysis needs)
- Identify experimental information/efficiencies to characterize response to your objects and observables (i.e. Can use open data/HEPData)

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



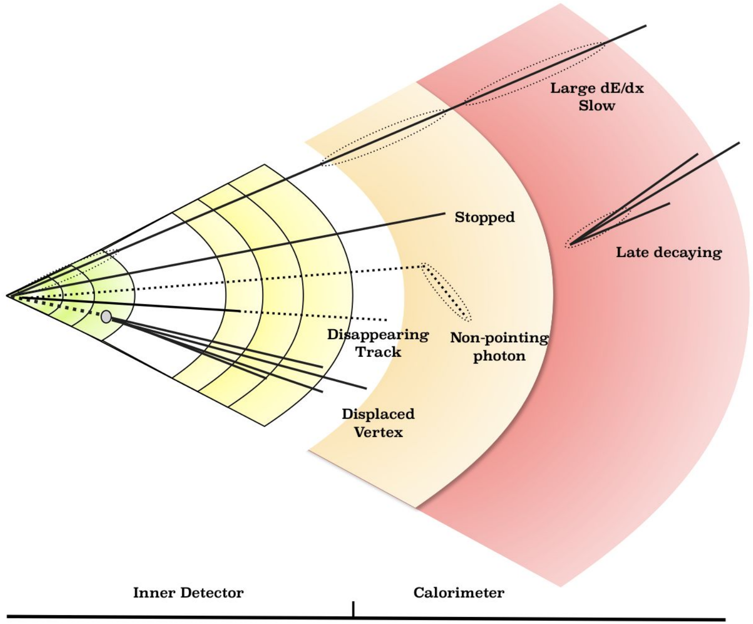


Image by Heather Russel (based on ATLAS geometry)
Long-lived Particle Community Workshop, 2017

Image by G. Cottin

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

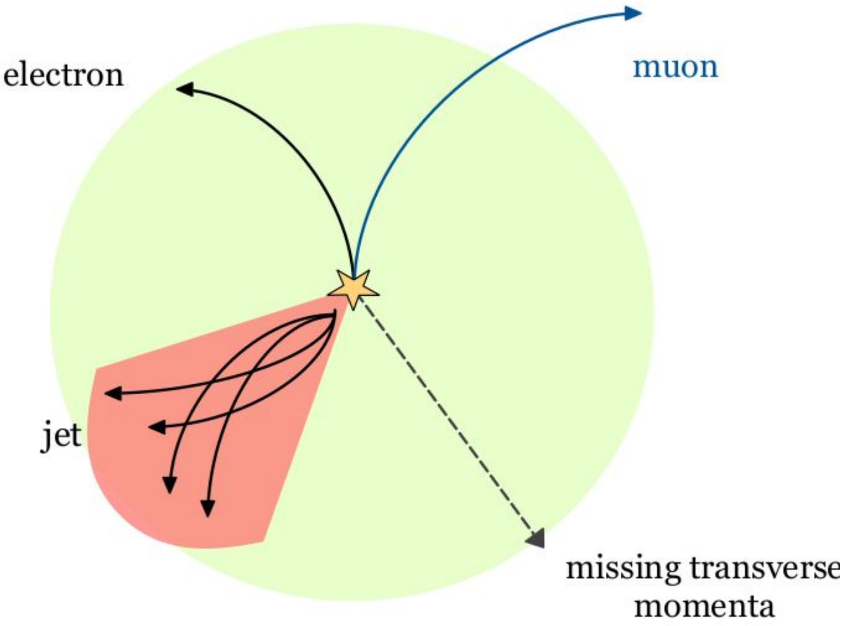
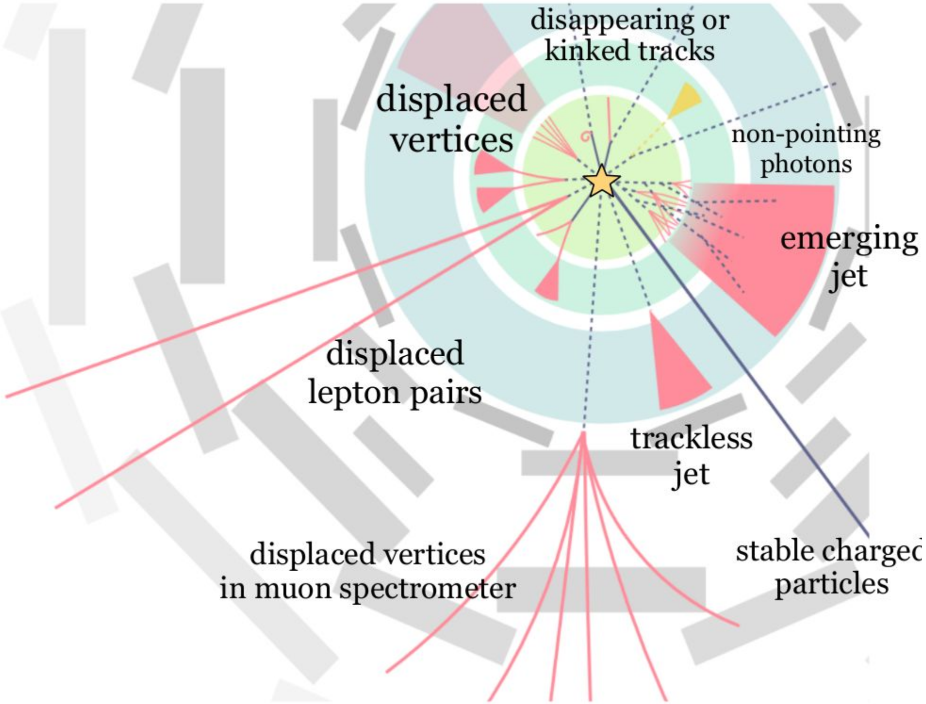


Image by G. Cottin

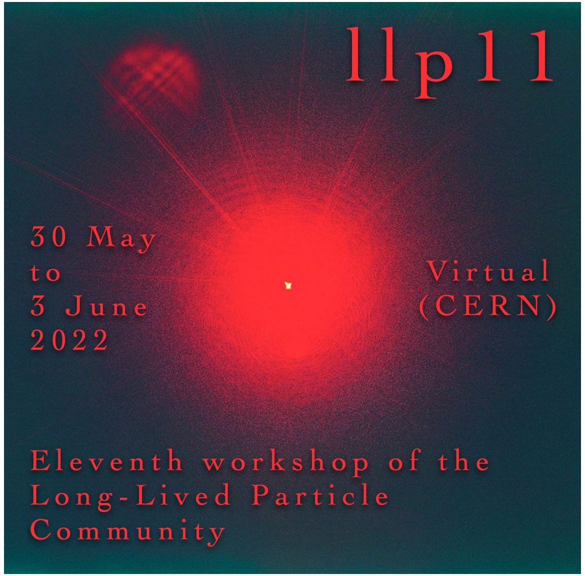


LLP Image adapted from Heather Russel.

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

Many LLP efforts worldwide ! Formally an LHC LLP Working Group at CERN

LLP Community https://cern.ch/longlivedparticles
LLP WG https://lpcc.web.cern.ch/lhc-llp-wg



Activities within LLP Community and WG (whitepaper, regular workshops, recasting repo)
You can subscribe to LLP-WG egroup !
LLP Community White Paper arXiv:1903.04497
LLP repo https://github.com/llprecasting/recastingCodes

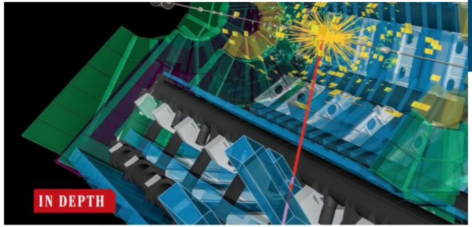
SnowMass2021

WELCOME PAGE
ANNOUNCEMENTS
SNOWMASS CALENDAR
ETHICS GUIDELINES
- Organization

EF09 - BSM: More general explorations

Table of Contents
- EF09 - BSM: More general explorations
  - Group Topics
  - Meetings
  - Contacts
  - Submitted LOI

Conveners | Tulika Bose, Zhen Liu, Simone Pagan Griso (more contact info)



In a simulated event, the track of a decay particle called a muon (red), displaced slightly from the center of particle collisions,

PARTICLE PHYSICS

A hunt for long-lived particles ran

The Large Hadron Collider could be making new particles that are

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 ...

It's a push ... menters at ... the Higgs b...

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, ...

of sub... particl... energie... ing an... muons... where... lide. 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 ... such oddities are mistakes a... Tova Holmes, an ATLAS me... University of Chicago in ... searching for the displaced ...

CERN Accelerating science — Sign in

LPCC
LHC Physics Centre at CERN

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LHC LLP WG: Long-lived Particles at the LHC

To subscribe to the general WG mailing list, used to distribute announcements about WG meetings and available documents, go to http://simba3.web.cern.ch/simba3/SelfSubscription.aspx?groupName=lhc-llpwg

Mandate:

The LHC Long-lived Particles Working Group (LHC LLP WG) brings together experimentalists and theorists to discuss the physics of new long-lived particles at the LHC. It also covers physics with unconventional experimental signatures. The WG builds on the experience of the LLP LHC Community and, preserving its main scientific objectives, it serves as a formal bridge with the relevant physics groups of the LHC experiments, to streamline the official endorsement of the WG's recommendations to the experiments. The WG will hold open meetings, typically at CERN, complementing the Workshops organized by the LLP LHC Community. The formation of dedicated subgroups, and possible closed meetings (restricted

Dark Matter WG
- WG documents
- WG Meetings

Electroweak WG
- WG Documents
- WG meetings

Forward Physics WG
- WG documents
- WG meetings

Adding your recasting code

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

Repository Structure

The repository folder structure is organized according to the type of LLP signature and the ... 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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SEARCHES FOR NEW PHYSICS | MEETING REPORT

Long-lived particles gather interest

21 July 2021

Formally an LHC LLP Working Group at CERN

CERN Accelerating science   Sign in

LPCC
LHC Physics Centre at CERN

ABOUT LHC WGS LHC PUBLICATIONS EVENTS NEWSLETT

LHC LLP WG: Long-lived Particles at the LHC

To subscribe to the general WG mailing list, used to distribute announcements about WG meetings and available documents, go to http://simba3.web.cern.ch/simba3/SelfSubscription.aspx?groupName=lhc-llpwg

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- WG meetir

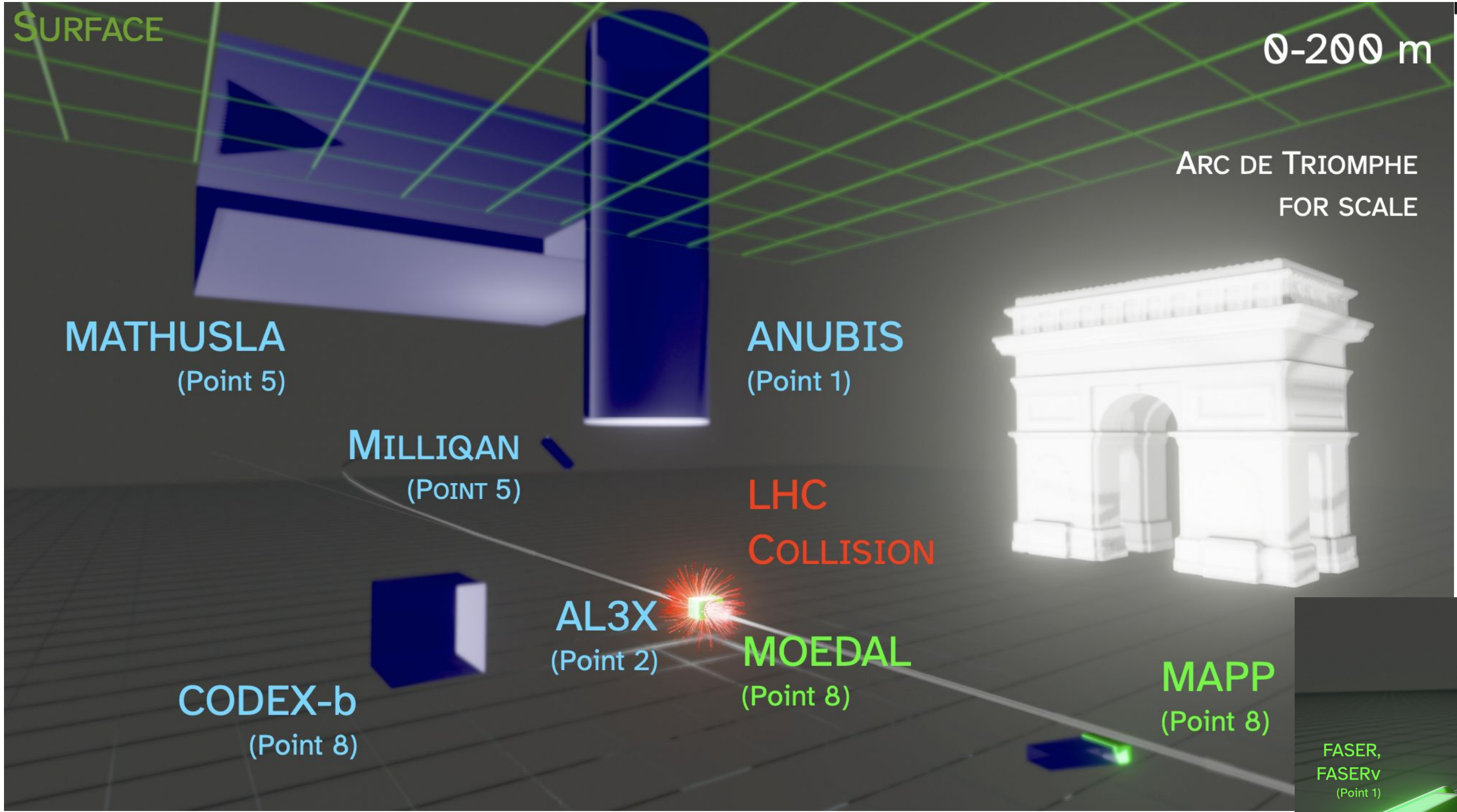
https://lpcc.web.cern.ch/lhc-llp-wg

You can get in touch and/or subscribe to the mailing list for news !

Main goals are:
- Facilitate communication between theorist and experimentalists
- Provide recommendation for benchmark models to be used in LLP interpretation
- Provide recommendation for presentation of experimental results in a useful way for reinterpretation
- Discuss new search directions based on new input from theory or experiment

Conveners:
- ATLAS: Simone Pagan Griso and Emma Torro Pastor
- CMS: Alberto Escalante del Valle and Larry Lee
- FASER: Dave Casper
- LHCb: Federico Leo Redi and Carlos Vázquez Sierra
- MoEDAL: James Pinfold
- SND@LHC: Cristovao Vilela
- Theory: Giovanna Cottin, Nishita Desai and José Zurita
- Reach all through lhc-llpwg-admin@cern.ch

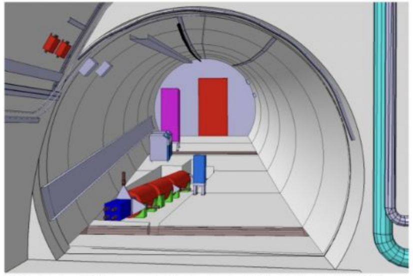
Even new approved/proposed LLP experiments

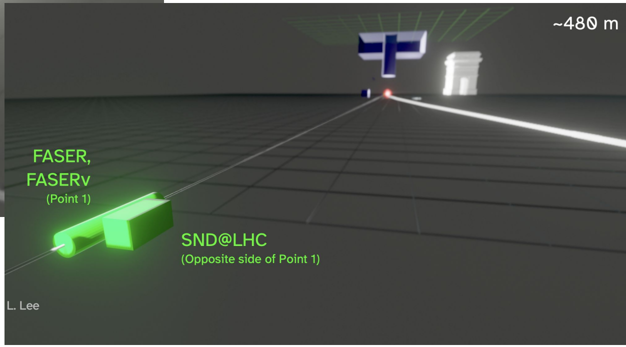


FASER: CERN approves new experiment to look for long-lived, exotic particles

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

7 MARCH, 2019 | By Cristina Agrigoroae



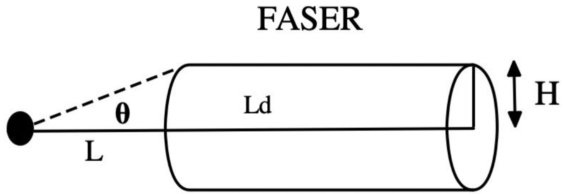


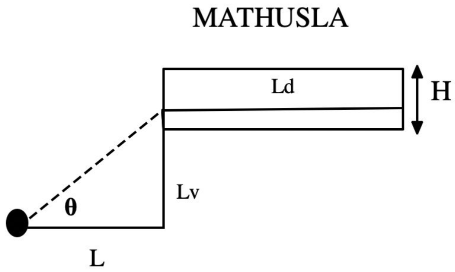
Slide from L. Lee @ LHCPC2021

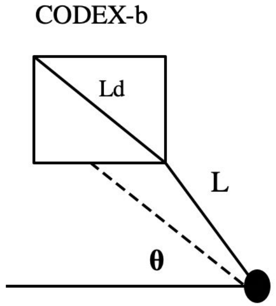
https://indico.cern.ch/event/905399/contributions/4282550/attachments/2261167/3837992/060921_LLee_NeutralFIPs.pdf

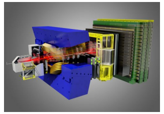
Phenomenology with displaced decays at LLP detectors

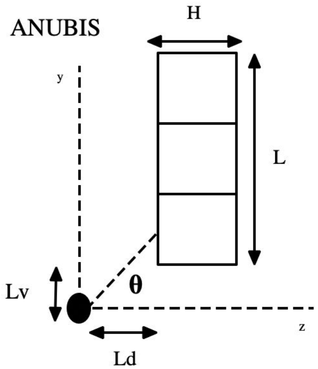
Decay probability of each simulated HNL takes into account the far detector geometry (L, Ld, Lv, H, θ) and their kinematics

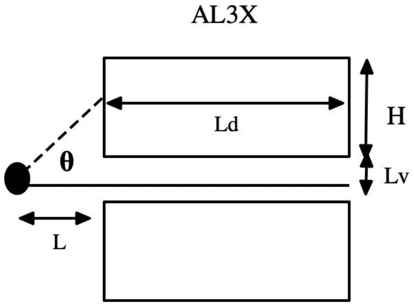


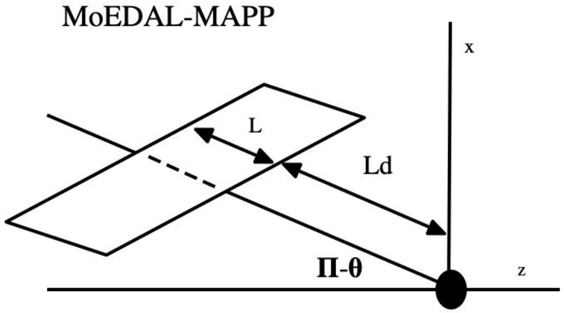












Details of probability of decay formulas in fiducial volumes
See Jordy de Vries, H. K. Dreiner, J. Y. Günther, Z. S. Wang, G. Zhou, 2010.07305 (JHEP 03 (2021))
For FASER, MATHUSLA and CODEX-b see D. Dercks, J. de Vries, H. K. Dreiner, Z. S. Wang, 1810.03617 (Phys. Rev. D 99, 055039 (2019)) *and earlier 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))

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

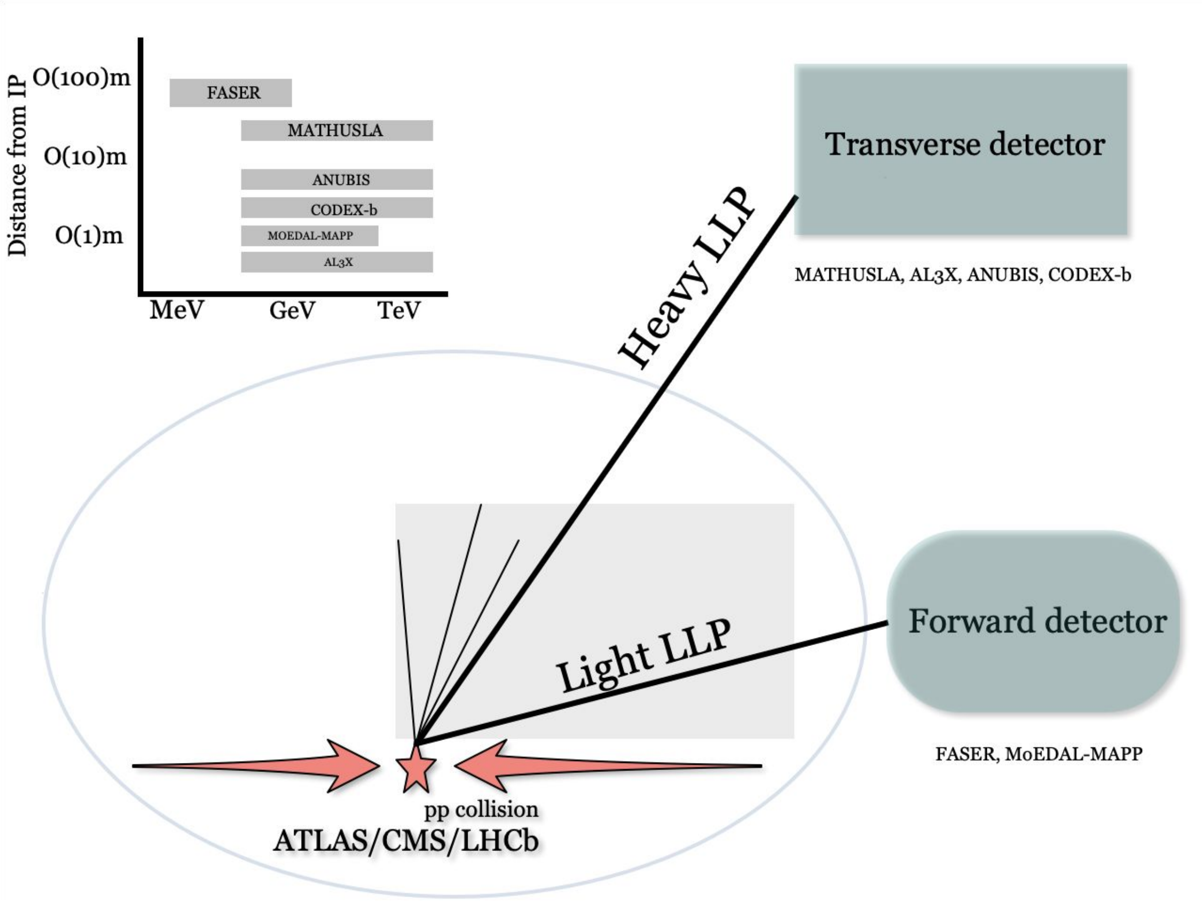
MAPP1: ~ 130 m^3

MAPP2: ~ 430 m^3

$c\tau \sim 50$ m

With thanks to A. Titov

Many LLP experiments 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

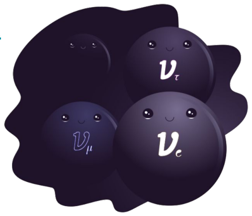
HNL LLP Motivation

An answer for neutrino mass generation mechanism

See review in A. Atre, T. Han, S. Pascoli, B. Zhang, JHEP 05 (2009) 030, arXiv:0901.3589

Could also explain Dark Matter and Baryon Asymmetry

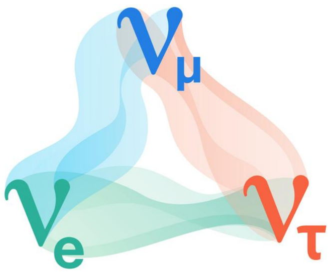
T.Asaka, M.Shaposhnikov, PL B620 (2005), hep-ph/0505013
See reviews in A. Boyarsky, et al., Prog. in Part. and Nucl. Phys. 104 (2019), arXiv:1807.07938,
A. Boyarsky, O. Ruchayskiy, M. Shaposhnikov, Ann.Rev.Nucl.Part.Sci. 59 (2009), arXiv: 0901.0011



@symmetrymagazine

Known

- Neutrino oscillations therefore neutrinos in the SM have mass



See P. F. de Salas et al., JHEP 02 (2021) 071, arXiv:2006.11237

Unknown

- Neutrino mass mechanism involving HNL (i.e seesaw mechanism, inverse seesaw, …)
- Specific BSM Model of neutrino mass generation (i.e new interactions of HNL beyond Yukawa ones?)
- HNL nature (Dirac or Majorana)
- HNL mass scale

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)
Inverse seesaw
R. Mohapatra and J. Valle, Phys. Rev. D34 (1986) 1642

Seesaw Mechanism(s)

- Predicts HNLs
- HNLs mix with SM neutrinos
- Can be realised in many BSM models

@symmetrymagazine

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)

Inverse seesaw
R. Mohapatra and J. Valle, Phys. Rev. D34 (1986) 1642

Minimal Type I Seesaw

Is not the only possibility … i.e Inverse Seesaw

$$\mathcal{L}_{\nu\,mass} = \frac{1}{2}\left(\overline{\nu_L^c}\ \overline{N_R}\right)\mathcal{M}_\nu\begin{pmatrix}\nu_L\\ N_R^c\end{pmatrix} + h.c$$

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

$M_N \gg m_D$

$$m_\nu \approx -m_D\cdot M_N^{-1}\cdot m_D^T$$

$$m_N \approx M_N$$

$$V_{\ell N} = m_D\cdot M_N^{-1} \Rightarrow V_{\ell N}^2 \sim m_\nu/M_N$$

$$V_{\ell N} = m_D\cdot M_N^{-1} \Rightarrow V_{\ell N}^2 \sim m_\nu/M_N$$

$$(\nu_L, N_R^c, S_L)$$

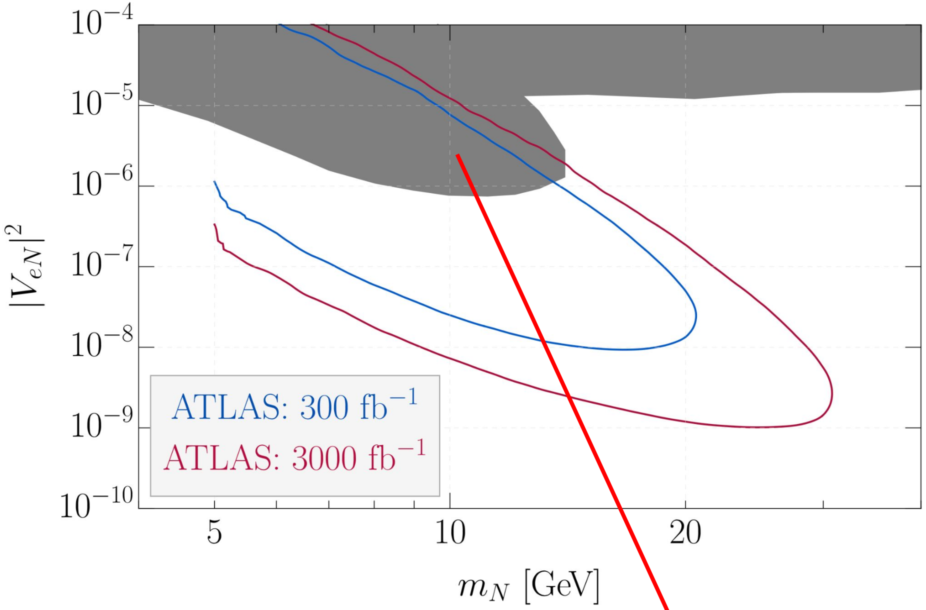
$$\mathcal{M}_\nu = \begin{pmatrix}0 & m_D^T & \epsilon^T\\ m_D & M & M_N\\ \epsilon & M_N^T & \mu\end{pmatrix}$$

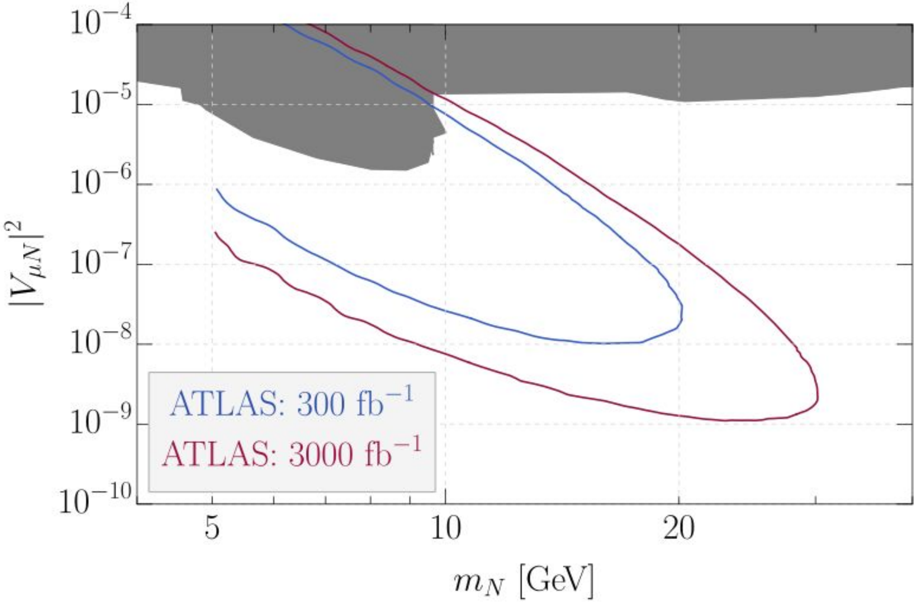
$\mu \ll M_N$ Inverse seesaw $\longrightarrow V_N^2 \sim m_\nu/\mu$

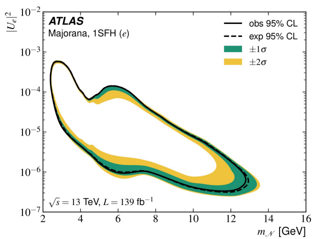
Pheno approach: consider HNL mass and mixing as independent parameters

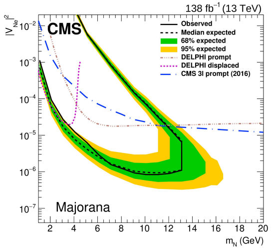
Sensitivity reach in minimal HNL model

R. Beltrán, G. Cottin, J.C. Helo, M. Hirsch, A. Titov, Z.S. Wang, JHEP 01 (2022) 044, [2110.15096]









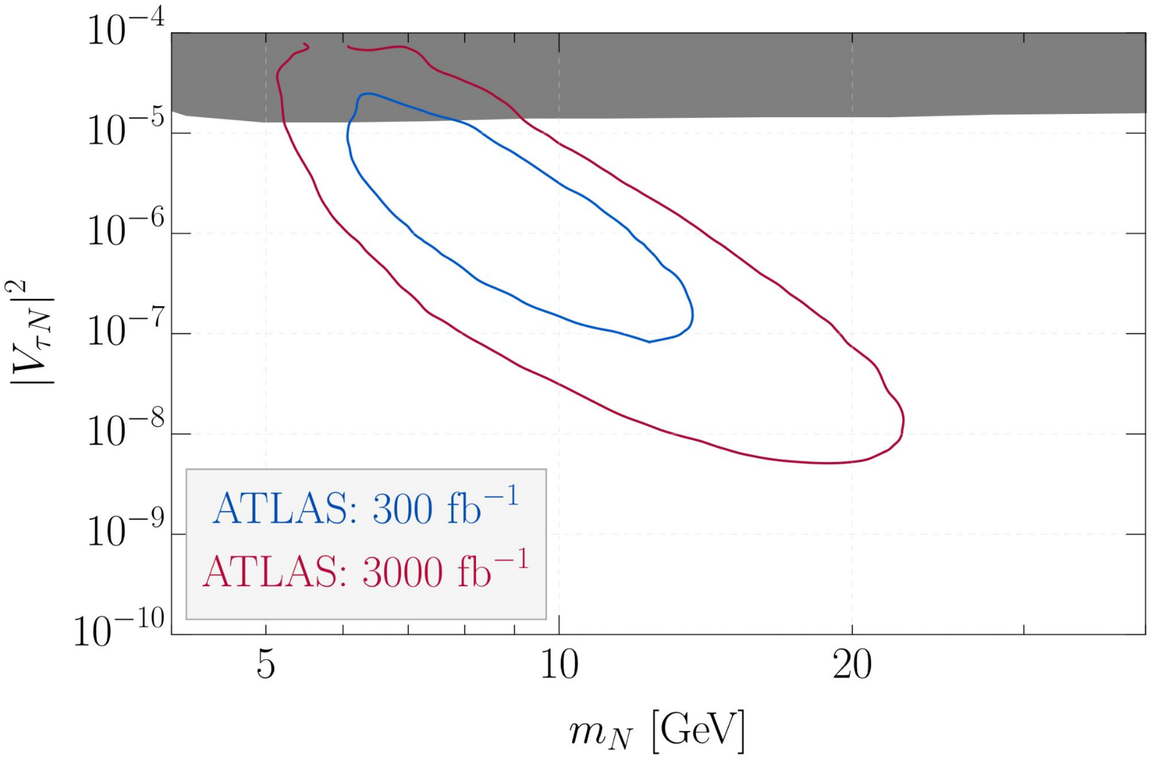
Latest LHC LLP HNL searches in [CMS PAS EXO-20-009], [EXOT-2019-29] consider prompt lepton triggers (i.e. electron or muon) and the identification of a displaced lepton vertex

Constraints in the electron/muon mixing plane vs HNL mass only

Tau-mixing not covered yet at LHC, what can we do?

1) Displaced Multitrack in inner trackers

R. Beltrán, G. Cottin, J.C. Helo, M. Hirsch, A. Titov, Z.S. Wang, JHEP 01 (2022) 044, 2110.15096



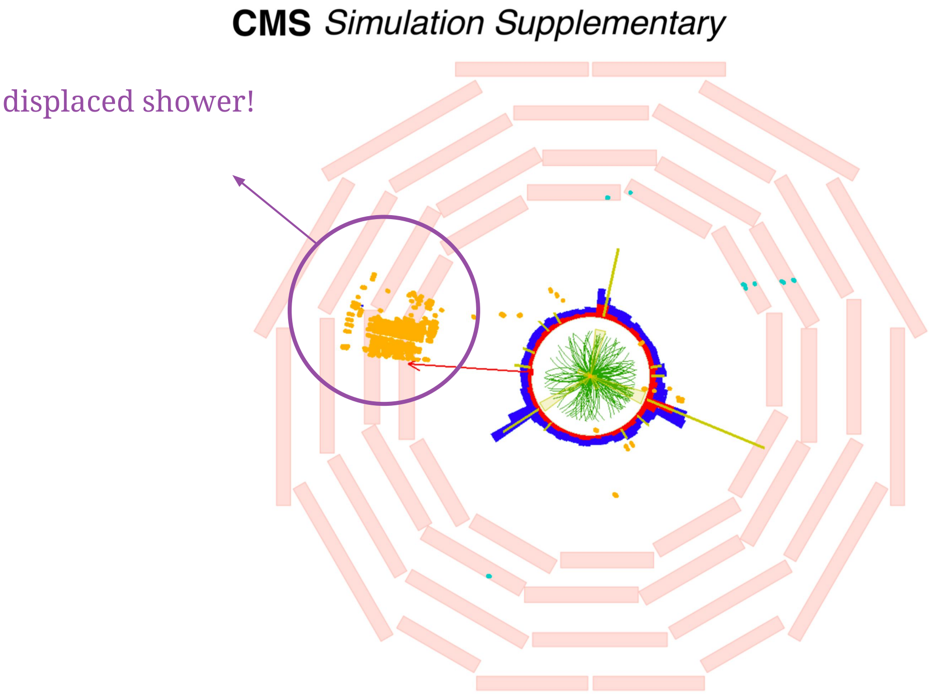
Displaced vertex searches with multitrack

- HNL decays leptonically and/or semileptonically
- prompt lepton trigger from W decay
- high-mass and displaced track multiplicity DVs in inner tracker to suppress hadronic bkgs.

Updated from G. Cottin, J.C. Helo and M. Hirsch, PRD 98 (2018),

Tau-mixing not covered yet at LHC, what can we do?

2) New signature of a displaced shower in the CMS muon system

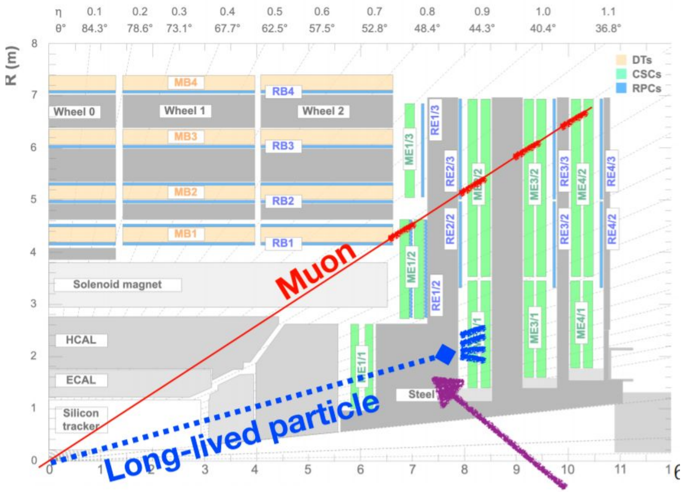


http://cms-results.web.cern.ch/cms-results/public-results/publications/EXO-20-015/

- We reinterpret* a search for a SM Higgs boson decaying to long-lived scalars (which can subsequently decay to taus), *Phy. Rev. Lett. 127 (2021)*, arXiv:2107.04838

- Search is sensitive to LLPs decaying to hadrons, *taus*, electrons, or photons. Large CMS steel shielding useful to suppress backgs.

- The CMS unique signature relies on large cluster of Cathode Strip Chamber (CSC) hits in the muon system (Nhits)



@ 7th LLP Workshop, see talk by Sven Dildick

* Reinterpretation relies on the implementation of a new Delphes module made specifically for muon system showers from LLP decays (https://github.com/delphes/delphes/pull/103)

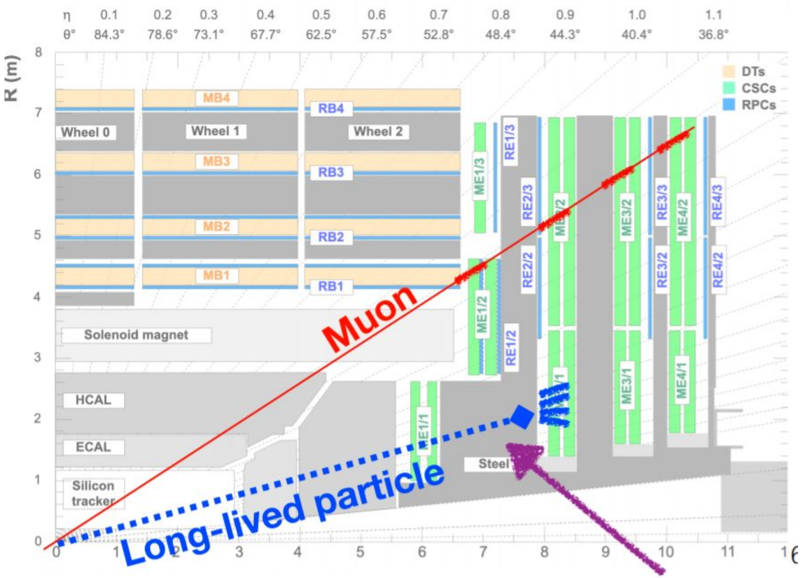
HNL optimized strategies

- Strategy 1 : Maintains high MET trigger but with a tighter Nhits cut.
  Nhits>210 suppresses background to 0.2 for 3/ab without rejecting too much signal (~20%)

- Strategy 2: Lower MET cut > 50 GeV and increased Nhits. Justified by the potential use of a new dedicated displaced trigger plan by CMS. See *Review of opportunities for new long-lived particle triggers in Run 3 of the Large Hadron Collider, CERN-LPCC-2021-01,* arXiv:2110.14675

  Nhits>290 (for 300/fb) and Nhits>370 (for 3/ab), optimized to control background to neglectable levels and increase signal acceptance (by ~ 3 orders of magnitude with respect to nominal MET and Nhit cuts).

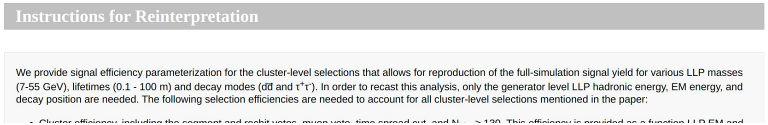
CMS presented a plan for a dedicated displaced L1 trigger for Run3 @ 7th LLP Workshop, see talk by Sven Dildick



- Reinterpretation relies on public instructions provided by CMS, as well as the implementation of a new Delphes module made specifically for muon system showers from LLP decays.

- Dedicated Delphes module presented by Christina Wang @ LLPX, see talk here.

http://cms-results.web.cern.ch/cms-results/public-results/publications/EXO-20-015/


Instructions for Reinterpretation

We provide signal efficiency parameterization for the cluster-level selections that allows for reproduction of the full-simulation signal yield for various LLP masses (7-55 GeV), lifetimes (0.1 - 100 m) and decay modes ($d\bar{d}$ and $\tau^+\tau^-$). In order to recast this analysis, only the generator level LLP hadronic energy, EM energy, and decay position are needed. The following selection efficiencies are needed to account for all cluster-level selections mentioned in the paper:

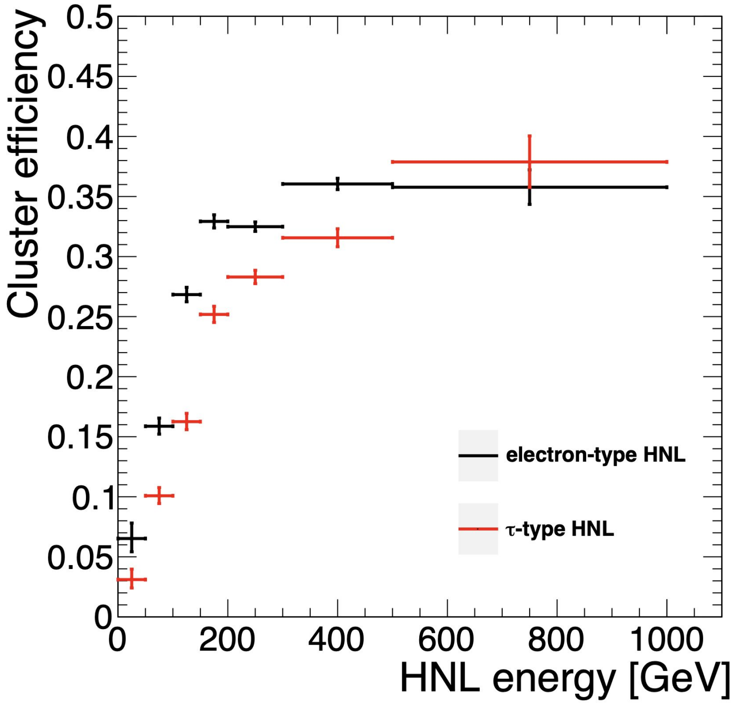
Recasted analysis and simulations

HeavyN model -> Madgraph+Pythia8 -> (tuned) Delphes (https://github.com/delphes/delphes/pull/103). Generator-level HNL energy and decay position are needed for signal yield prediction

Analysis selections:

- MET ≥ 200 GeV
- 1 CSC cluster that passes the CSCClusterEfficiency and CSCClusterID module (which includes Nhits> 130 and encodes parameterized functions depending on LLP energy and decay region provided by CMS)
- Jet veto, time cut and $|\Delta\varphi(\text{cluster, MET})|<0.75$

G.Cottin, J.C. Helo, M. Hirsch, C. Peña, C. Wang, S. Xie (2210.17446)

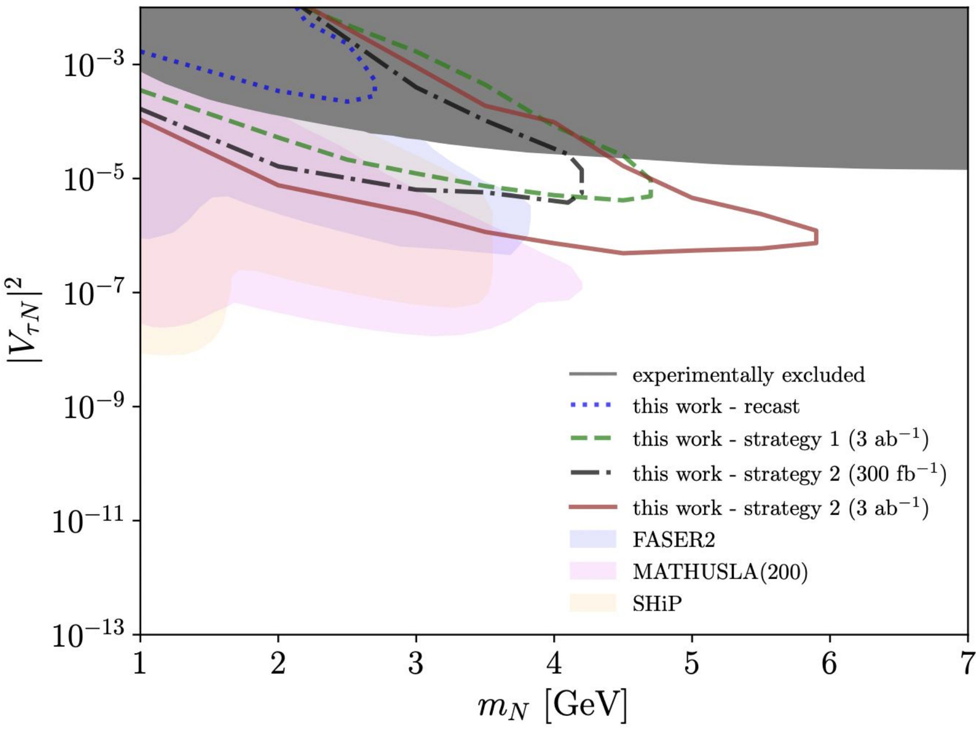


FeynRules HNL implementation in
C. Degrande, O. Mattelaer, R. Ruiz, J. Turner, Phys. Rev. D 94, 053002 (2016), arXiv:1602.06957

Tau-mixing not covered yet at LHC, what can we do?

2) New signature of a displaced shower in the CMS muon system

G.Cottin, J.C. Helo, M. Hirsch, C. Peña, C. Wang, S. Xie (2210.17446)

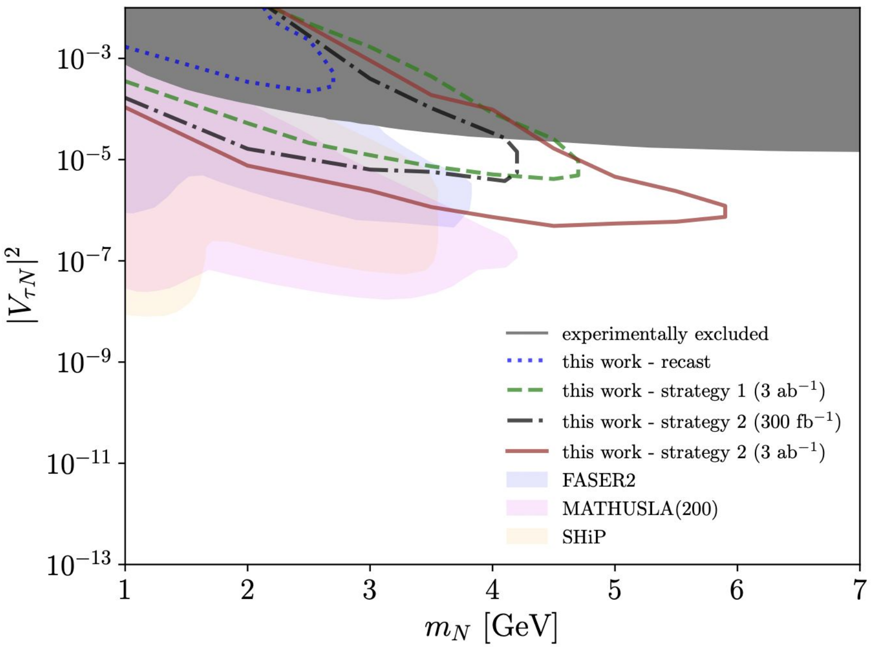


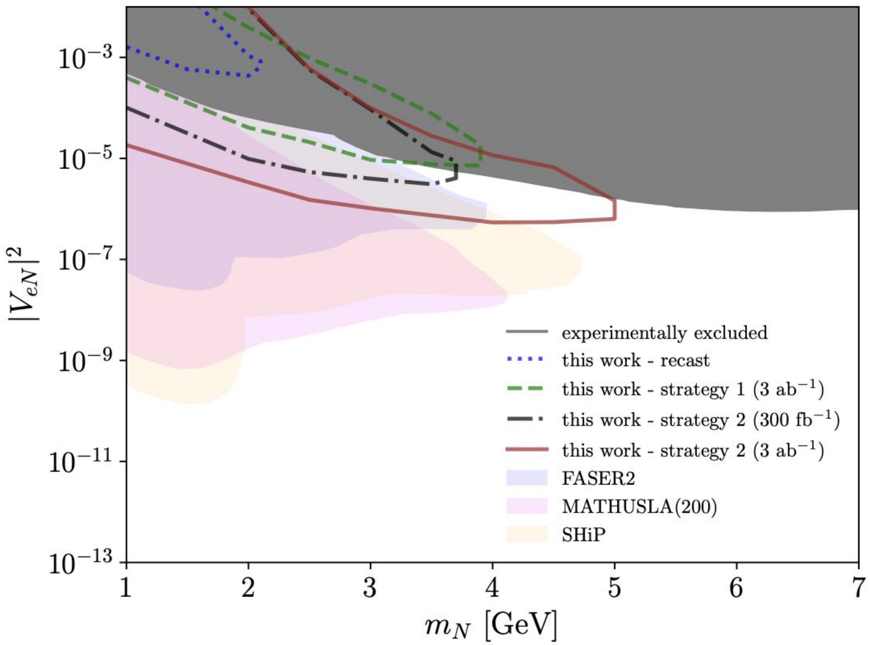
We proposed two HNL optimized strategies (for HNLs decaying to taus) by tuning search cuts

on MET and Nhits, with a potential new displaced trigger to be implemented at CMS. See *Review of opportunities for new long-lived particle triggers in Run 3 of the Large Hadron Collider, CERN-LPCC-2021-01,* arXiv:2110.14675

Results for tau and electron sector

G.Cottin, J.C. Helo, M. Hirsch, C. Peña, C. Wang, S. Xie (2210.17446)

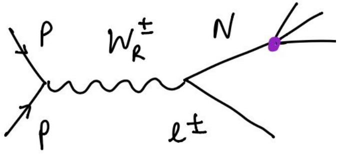




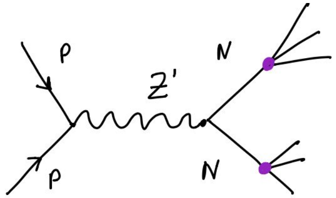
Beyond the minimal HNL model

Other LLP HNL displaced search strategies have been proposed that can be sensitive to non-minimal HNL models with additional production modes via e.g. new gauge bosons *(Z', WR)*

Can have DVs with no additional prompt objects
(highlighting critical need for dedicated displaced triggers)

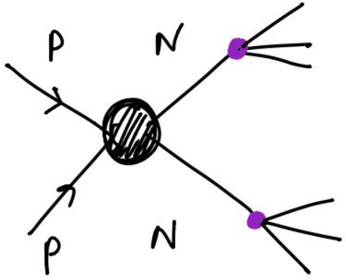


For Left-Right, see e.g.
G. Cottin, J.C. Helo, M. Hirsch, D. Silva, PRD 99 (2019)
G. Cottin, J.C. Helo, M. Hirsch, PRD 97 (2018)
M. Nemevšek, F. Nesti, G. Popara, PRD 97, (2018)



For B-L, see e.g.
C.-W. Chiang, G. Cottin et. al, JHEP 12 (2019), F. Deppisch et al., PRD 100 (2019),
F. Deppisch et al., JHEP 08 (2018) , B. Batell et al., JHEP08(2016)

A systematic way to study such non-minimal HNLs is to apply effective field theory (EFT)

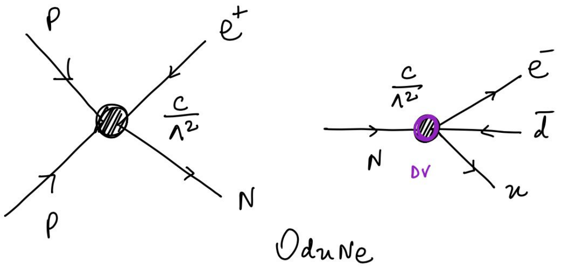


For HNLs in EFT with LLPs at the LHC, see e.g.
R.Beltrán, G. Cottin, J.C. Helo, M. Hirsch, A. Titov, Z.S. Wang, JHEP 01 (2023) 015
G. Cottin, J. C. Helo, M. Hirsch, A. Titov, Z. S. Wang, JHEP 09 (2021) 039
Jordy de Vries, H. K. Dreiner, J. Y. Günther, Z. S. Wang, G. Zhou, JHEP 03 (2021)
A. Caputo, P. Hernandez, J. Lopez-Pavon, J. Salvado, JHEP 06 (2017)

N_RSMEFT

d=6 four-fermion operators with *a single* HNL (2110.15096)

- Production and decay dominated by the operator
- Operators with Λ above ~ 1 TeV make the HNL long-lived



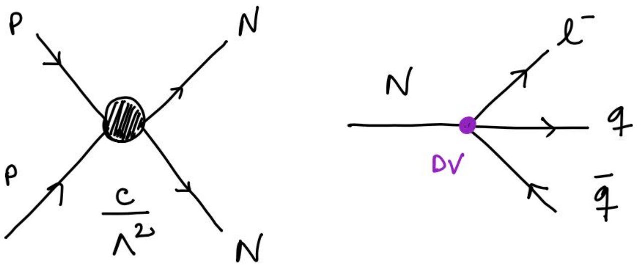
DV strategy in the inner trackers of LHC main detectors

- Reconstruction of a prompt isolated lepton (e, μ, τ)
- HNL decays via the operator leading to two jets and one neutral or charged lepton
- At least one high-mass and displaced track multiplicity DV in inner tracker (to suppress hadronic bkgs.)

$$\Gamma(N_R \to \ell q q') = \frac{c_O^2}{f_O} \frac{m_N^5}{512\pi^3 \Lambda^4}$$

d=6 four-fermion operators with *pairs* of HNL (2105.13851)

- Production dominated by the operator
- HNLs decay only via their mixing with the active neutrinos



DV strategy in the inner trackers of LHC main detectors.
Probability of displaced decay in fiducial volume in far detectors

- HNL decays via mixing leptonically and/or semileptonically. We consider *N->ejj*
- Non-isolated electrons with high pT truth-matched to lepton index from DV. At least one high-mass and displaced track multiplicity DV in inner tracker
- For far detectors, the decay probability of each simulated HNL in the fiducial volume is computed

$$\Gamma \sim G_F^2 \, m_N^5 \, |V_{eN}|^2$$

Beyond the minimal HNL model. NR_SMEFT offers a systematic way to study non-minimal HNL models, with NRO which are suppressed by a new physics scale Λ

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

d=6 four-fermion operators with *a single* HNL

R. Beltrán, G. Cottin, J.C. Helo, M. Hirsch, A. Titov, Z.S. Wang, 2110.15096 (JHEP 01 (2022) 044)

Name	Structure (+ h.c.)	$n_N = 1$	$n_N = 3$
$\mathcal{O}_{duNe}$	$(\overline{d_R}\gamma^\mu u_R)(\overline{N_R}\gamma_\mu e_R)$	54	162
$\mathcal{O}_{LNQd}$	$(\overline{L}N_R)\epsilon(\overline{Q}d_R)$	54	162
$\mathcal{O}_{LdQN}$	$(\overline{L}d_R)\epsilon(\overline{Q}N_R)$	54	162
$\mathcal{O}_{LNLe}$	$(\overline{L}N_R)\epsilon(\overline{L}e_R)$	54	162
$\mathcal{O}_{QuNL}$	$(\overline{Q}u_R)(\overline{N_R}L)$	54	162

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

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

G. Cottin, J. C. Helo, M. Hirsch, A. Titov, Z. S. Wang, 2105.13851, (JHEP 09 (2021) 039)

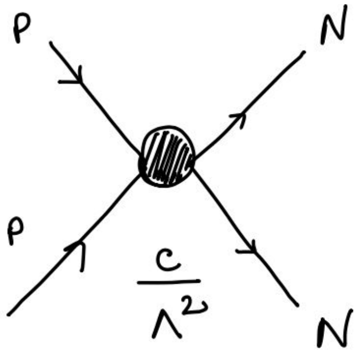
Name	Structure	$n_N = 1$	$n_N = 3$
$\mathcal{O}_{dN}$	$(\overline{d_R}\gamma^\mu d_R)(\overline{N_R}\gamma_\mu N_R)$	9	81
$\mathcal{O}_{uN}$	$(\overline{u_R}\gamma^\mu u_R)(\overline{N_R}\gamma_\mu N_R)$	9	81
$\mathcal{O}_{QN}$	$(\overline{Q}\gamma^\mu Q)(\overline{N_R}\gamma_\mu N_R)$	9	81
$\mathcal{O}_{eN}$	$(\overline{e_R}\gamma^\mu e_R)(\overline{N_R}\gamma_\mu N_R)$	9	81
$\mathcal{O}_{NN}$	$(\overline{N_R}\gamma_\mu N_R)(\overline{N_R}\gamma_\mu N_R)$	1	36
$\mathcal{O}_{LN}$	$(\overline{L}\gamma^\mu L)(\overline{N_R}\gamma_\mu N_R)$	9	81

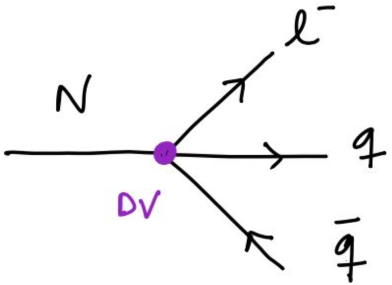
Additional HNLs in EFT with LLPs at the LHC studies
d=5 in A. Caputo, P. Hernandez, J. Lopez-Pavon, J. Salvado, JHEP 06 (2017)
Jordy de Vries, H. K. Dreiner, J. Y. Günther, Z. S. Wang, G. Zhou, JHEP 03 (2021)
R.Beltrán, G. Cottin, J.C. Helo, M. Hirsch, A. Titov, Z.S. Wang, JHEP 01 (2023)

N_RSMEFT sensitivity with displaced vertices

For *d=6* four-fermion operators with *pairs* of HNL G. Cottin, J. C. Helo, M. Hirsch, A. Titov, Z. S. Wang, 2105.13851, (JHEP 09 (2021) 039)

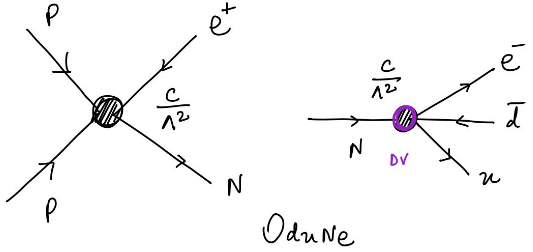
- Production dominated by the operator
- HNLs decay only via their mixing with the active neutrinos
- DV strategy proposed for ATLAS inner tracker
- Probability of displaced decay in fiducial volume in far detectors (extending model space coverage)





d=6, diff. mass regime in R.Beltrán, G. Cottin, J.C. Helo, M. Hirsch, A. Titov, Z.S. Wang, JHEP 01 (2023)

N_RSMEFT sensitivity with displaced vertices

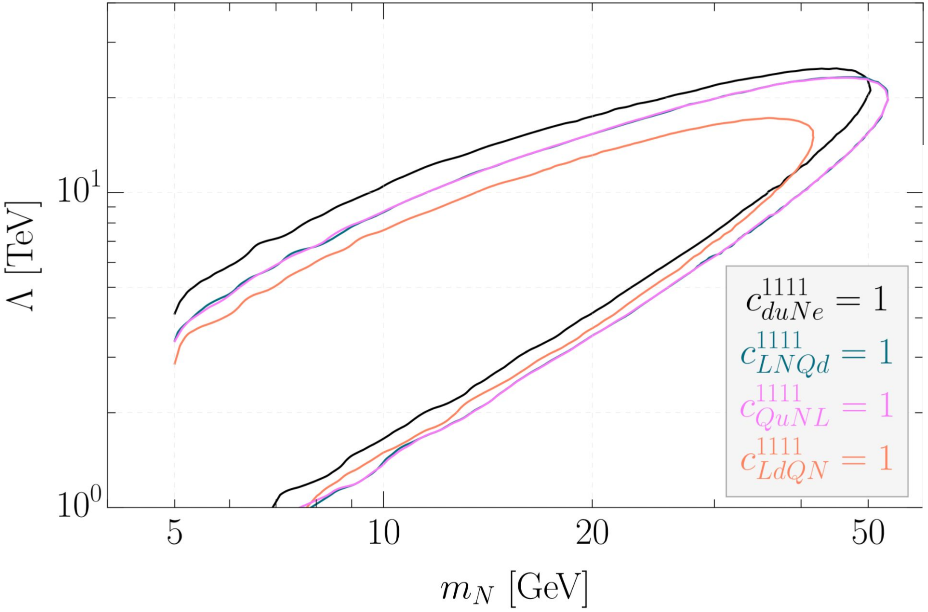


d=6 four-fermion operators with *a single* HNL

R. Beltrán, G. Cottin, J.C. Helo, M. Hirsch, A. Titov, Z

2110.15096 (JHEP 01 (2022) 044)

Production and decay dominated by the operator. Operators with Λ above ~ 1 TeV make the HNL long-lived



New physics scales in excess of ~20 TeV could be probed at the LHC with 3ab-1 for HNL masses ~50 GeV for operators with electrons and muons

New physics scales ~10 TeV could be probed for operators with taus