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

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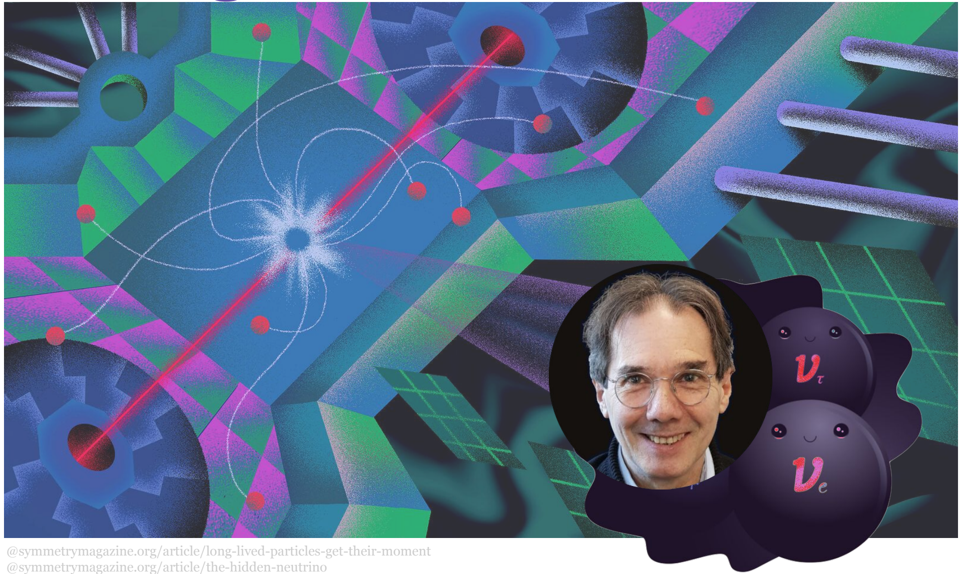
A long-lived collaboration



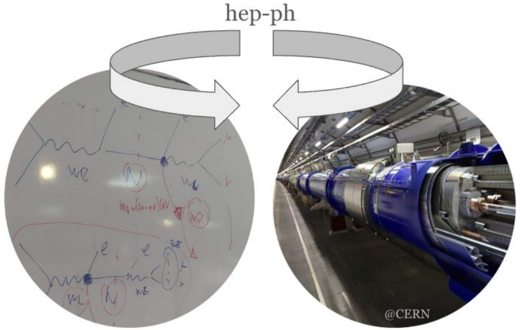
@symmetrymagazine.org/article/long-lived-particles-get-their-moment
@symmetrymagazine.org/article/the-hidden-neutrino

Giovanna Cottin
Pontificia Universidad Católica de Chile & SAPHIR Millennium Institute, Chile

Hirschfest, IFIC Valencia, January 24, 2024

We have worked on long-lived particles predicted in neutrino mass models for 7 years

nobelprize.org



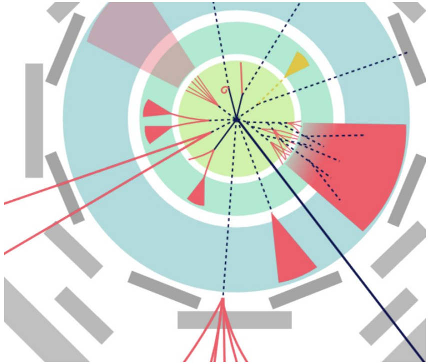


Image by H. Russel

Theory

Exotic signatures

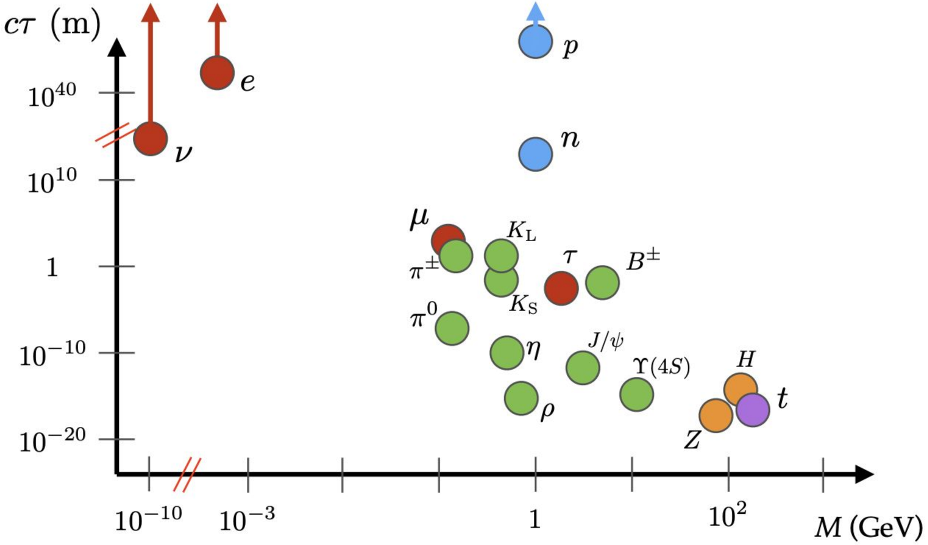


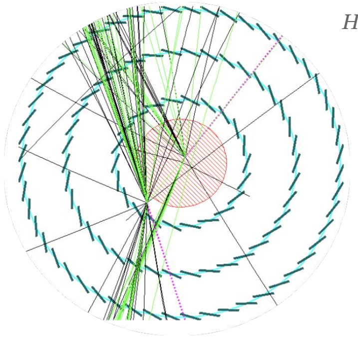
Image by B.Shuve

LLP = a new BSM particle with

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

2017-2018 Long-lived Heavy Neutral Leptons

HNL DV Strategy first proposed in G. Cottin, J.C. Helo and M. Hirsch, [PRD 97 (2018)]



PHYSICAL REVIEW D **97,** 055025 (2018)

Searches for light sterile neutrinos with multitrack displaced vertices

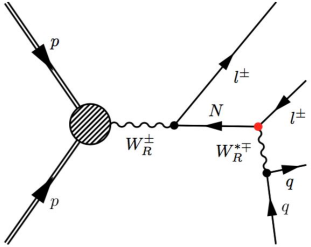
Giovanna Cottin*
Cavendish Laboratory, University of Cambridge, Cambridge CB3 0HE, United Kingdom and Department of Physics, National Taiwan University, Taipei 10617, Taiwan

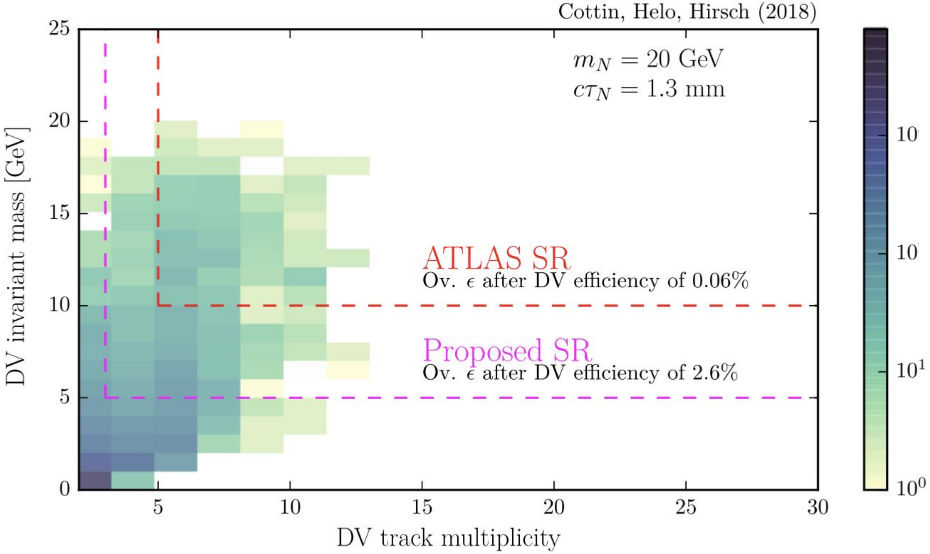
Juan Carlos Helo†
Departamento de Física, Facultad de Ciencias, Universidad de La Serena, Avenida Cisternas 1200, La Serena, Chile and Centro-Científico-Tecnológico de Valparaíso, Casilla 110-V, Valparaíso, Chile

Martin Hirsch‡
AHEP Group, Instituto de Física Corpuscular - C.S.I.C./Universitat de València, Edificio de Institutos de Paterna, Apartado 22085, E–46071 València, Spain

(Received 15 January 2018; published 16 March 2018; corrected 8 March 2019)

We study discovery prospects for long-lived sterile neutrinos at the LHC with multitrack displaced vertices, with masses below the electroweak scale. We reinterpret current displaced vertex searches making

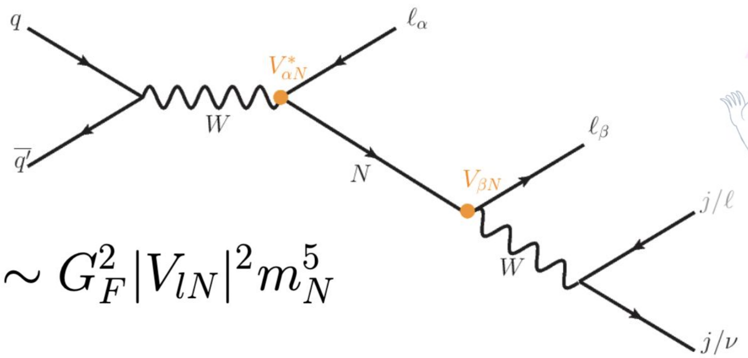




I had a look to the erratum. Nothing to add from my side.

Cheers,
Martin
ps: Only those, who do not do anything at all, make no mistakes. But it's the biggest mistake of all, not to do anything.

We then realized the same DV strategy is applicable to many models, and we've been refining it ever since



HNLs can be automatically long-lived!

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

G. Cottin, J.C. Helo and M. Hirsch, [PRD 98 (2018)]

PHYSICAL REVIEW D **98,** 035012 (2018)

Displaced vertices as probes of sterile neutrino mixing at the LHC

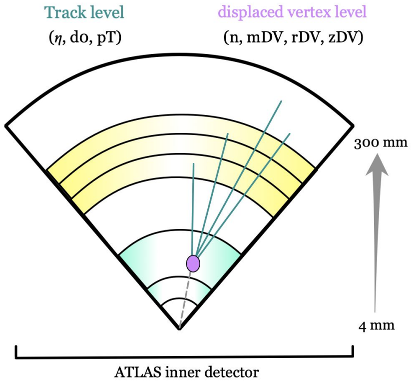
Giovanna Cottin*
Department of Physics, National Taiwan University, Taipei 10617, Taiwan

Juan Carlos Helo†
Departamento de Física, Facultad de Ciencias, Universidad de La Serena, Avenida Cisternas 1200, La Serena, Chile and Centro-Científico-Tecnológico de Valparaíso, Casilla 110-V, Valparaíso, Chile

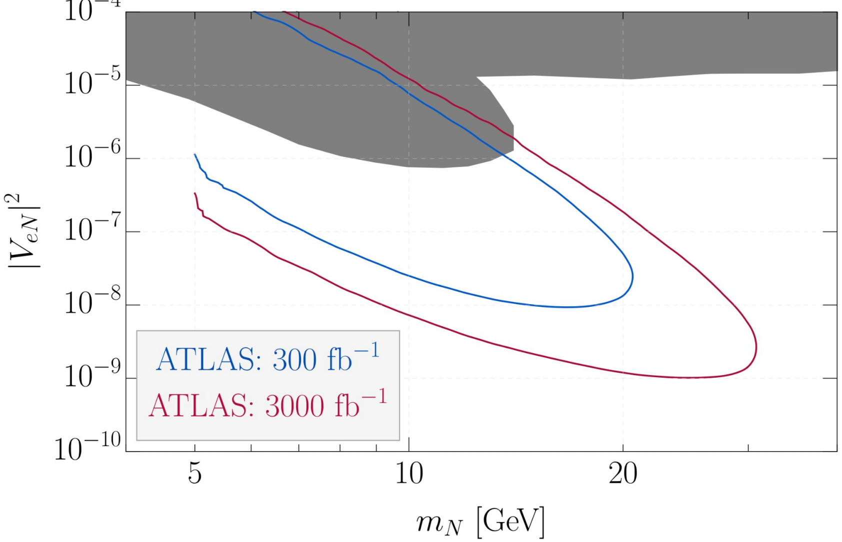
Martin Hirsch‡
AHEP Group, Instituto de Física Corpuscular—CSIC/Universitat de València, Edificio de Institutos de Paterna, Apartado 22085, E–46071 València, Spain

(Received 25 June 2018; published 8 August 2018)

We investigate the reach at the LHC to probe light sterile neutrinos with displaced vertices. We focus on sterile neutrinos N with masses $m_N \sim$ (5–30) GeV that are produced in rare decays of the standard model gauge bosons and decay inside the inner trackers of the LHC detectors. With a strategy that triggers on the

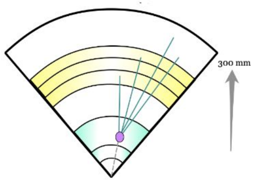


R. Beltrán, G. Cottin, J.C. Helo, M. Hirsch, A. Titov, Z.S. Wang, JHEP 01 (2022) 044, [2110.15096]



2019-2020

The LLP mania started ! ...

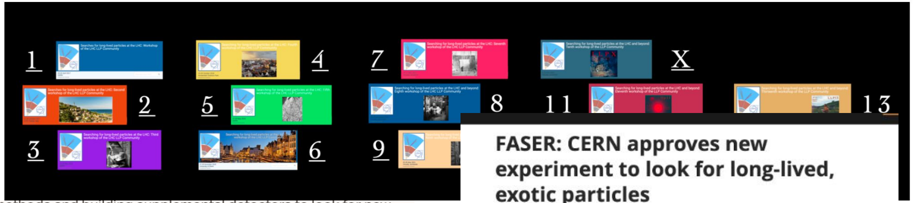


Science (2019)

Long-lived particles get their moment

methods and building supplemental detectors to look for new particles that might be evading them.

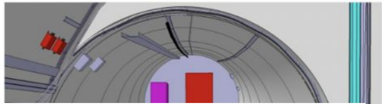
Long-Lived Particle Community Workshops

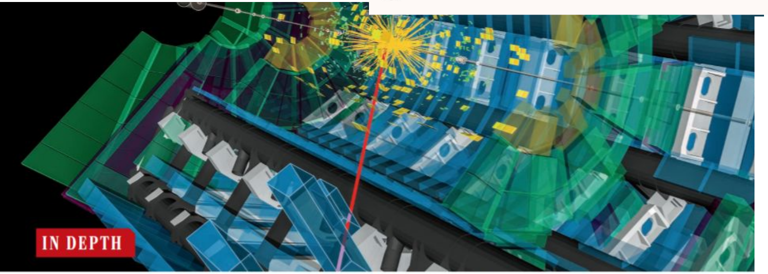


FASER: CERN approves new experiment to look for long-lived, exotic particles

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

7 MARCH, 2019 | By Cristina Agrigoroae





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 the Higgs boson, the last particle predicted

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 the existence of long-lived particles," she

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 people have written, basically rejects these

Journal of Physics G: Nuclear and Particle Physics

MAJOR REPORT • OPEN ACCESS

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

Juliette Alimena[1], James Beacham[2], Martino Borsato[3], Yangyang Cheng[4], Xabier Cid Vidal[5], Giovanna Cottin[6,7,8], David Curtin[9], Albert De Roeck[10], Nishita Desai[11], Jared A Evans[12] +

Published 2 September 2020 • © 2020 T

Journal of Physics G: Nuclear and P

Citation Juliette Alimena et al 2

DOI 10.1088/1361-6471/ab4

Long-lived charged particles and multi-lepton signatures from neutrino mass models #6
Carolina Arbeláez R (Santa Maria U., Valparaiso and CCTVal, Valparaiso), Giovanna Cottin (Adolfo Ibanez U.), Juan Carlos Helo (La Serena U.), Martin Hirsch (Valencia U., IFIC) (Mar 25, 2020)
Published in: *Phys.Rev.D* 101 (2020) 9, 095033 • e-Print: 2003.11494 [hep-ph]
pdf DOI cite claim reference search 12 citations

Revisiting the LHC reach in the displaced region of the minimal left-right symmetric model #7
Giovanna Cottin (Taiwan, Natl. Taiwan U.), Juan Carlos Helo (La Serena U.), Martin Hirsch (Valencia U.), Dario Silva (La Serena U.) (Feb 14, 2019)
Published in: *Phys.Rev.D* 99 (2019) 11, 115013 • e-Print: 1902.05673 [hep-ph]
pdf DOI cite claim reference search 15 citations

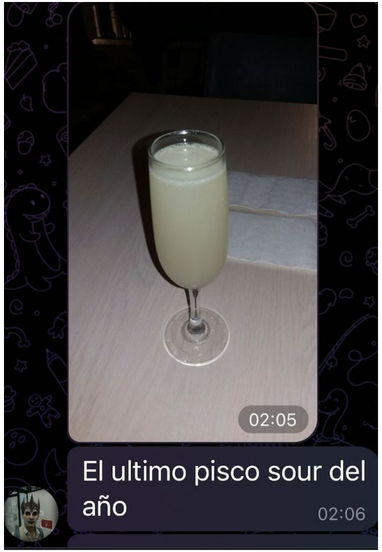
We were looking for LHC gaps in coverage and thinking of models predicting LLPs which were not yet tested !

A Hirsch on the hunt!

Growing collaborations with the Chileans ! …

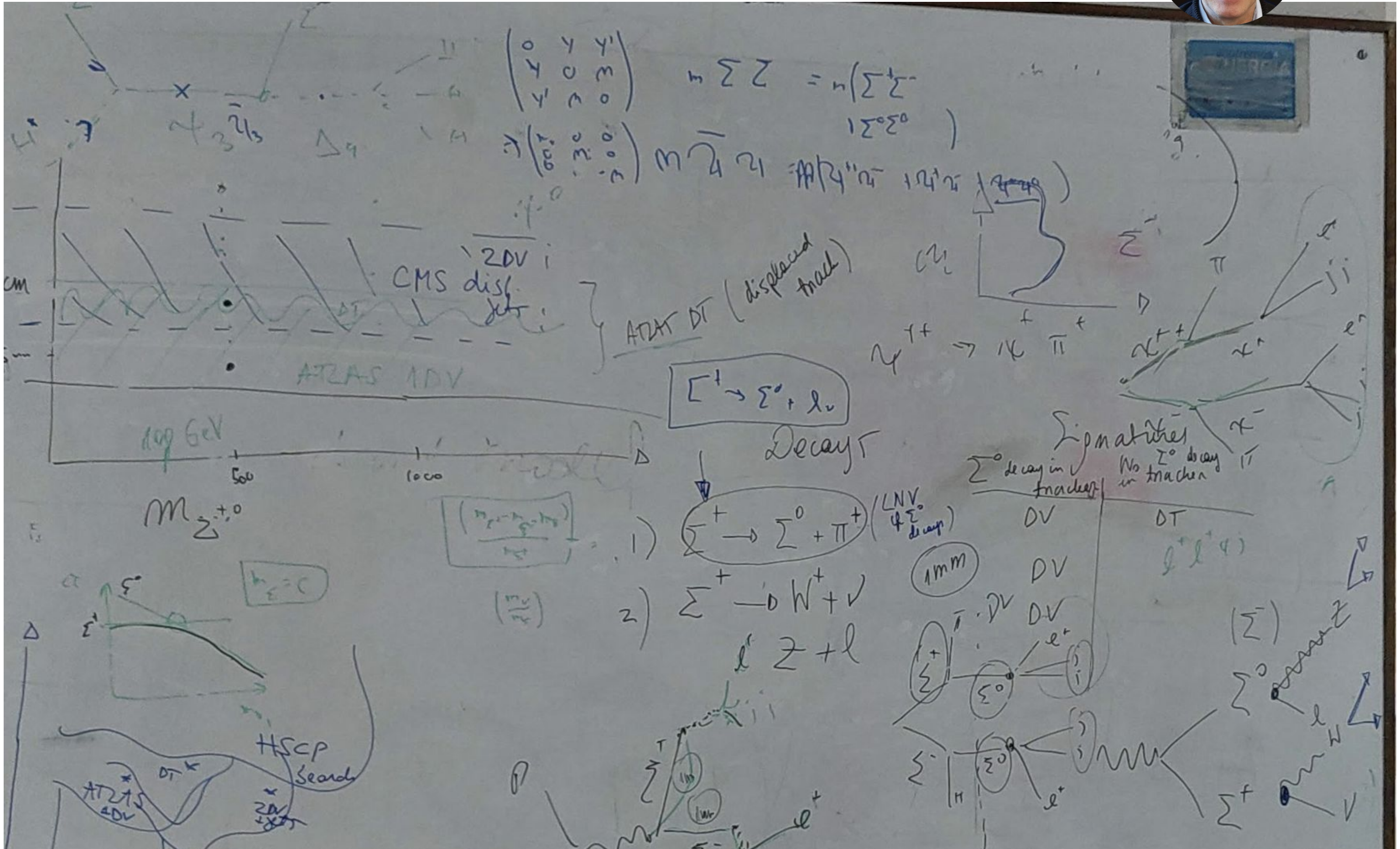
@ Chile 2019

… And pisco sour !…



But focused mostly on work :P

@ Chile 2019



2020 - 2021 - 2022

Along came a worldwide pandemic ...

- And a first faculty job for me (2020)
- And new collaborations !
- And a more systematic way to understand LLPs in neutrino mass models
- And many more lessons from Martin

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

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

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

$\mathcal{O}_{dN}$	$(\overline{d_R}\gamma^\mu d_R)\,(\overline{N_R}\gamma_\mu N_R)$
$\mathcal{O}_{uN}$	$(\overline{u_R}\gamma^\mu u_R)\,(\overline{N_R}\gamma_\mu N_R)$
$\mathcal{O}_{QN}$	$(\overline{Q}\gamma^\mu Q)\,(\overline{N_R}\gamma_\mu N_R)$

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

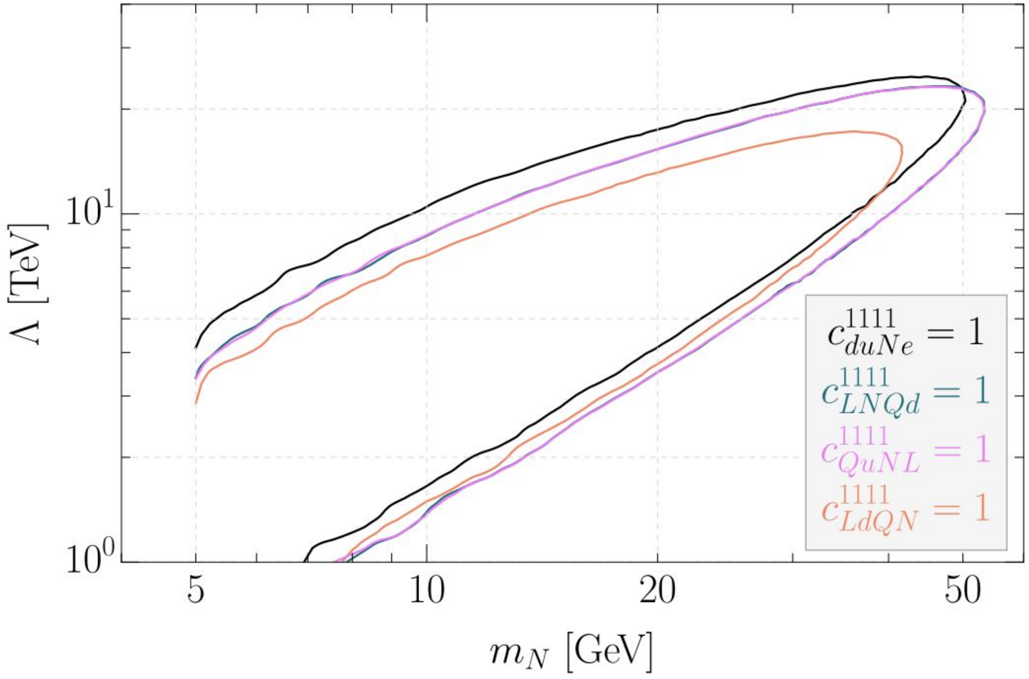
R. Beltrán, G. Cottin, J.C. Helo, M. Hirsch, A. Titov, Z.S. Wang, JHEP 01 (2022) 044

$\mathcal{O}_{duNe}$	$(\overline{d_R}\gamma^\mu u_R)\,(\overline{N_R}\gamma_\mu e_R)$
$\mathcal{O}_{LNQd}$	$(\overline{L}N_R)\,\epsilon\,(\overline{Q}d_R)$
$\mathcal{O}_{LdQN}$	$(\overline{L}d_R)\,\epsilon\,(\overline{Q}N_R)$
$\mathcal{O}_{QuNL}$	$(\overline{Q}u_R)\,(\overline{N_R}L)$

Example for operators with *a single* HNL

- Production and decay dominated by the operator
- LLP ATLAS inspired DV search can probe so-far uncharted parts of parameter space

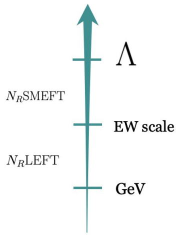
$$\Gamma(N_R \to \ell q q') = \frac{c_{\mathcal{O}}^2 m_N^5}{f_{\mathcal{O}} 512 \pi^3 \Lambda^4}$$



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

For operators with *pairs* of HNL G. Cottin, J. C. Helo, M. Hirsch, A. Titov, Z. S. Wang, JHEP 09 (2021) 039

2022 - 2023



$$\mathcal{L}_{N_R\mathrm{LEFT}} = \mathcal{L}_{\mathrm{ren}} + \sum_{d\geq 5}\sum_i c_i^{(d)}\mathcal{O}_i^{(d)}$$

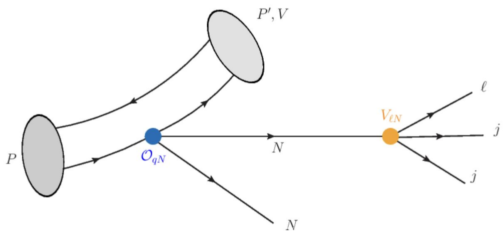
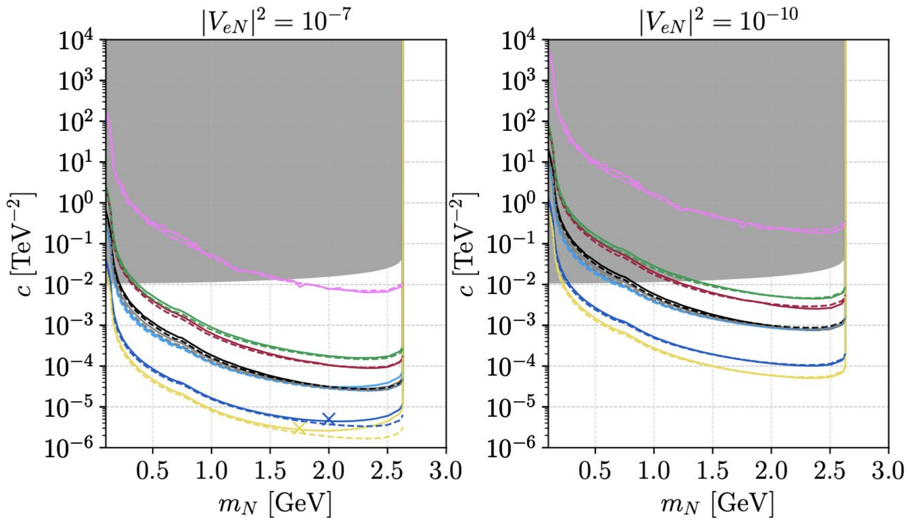


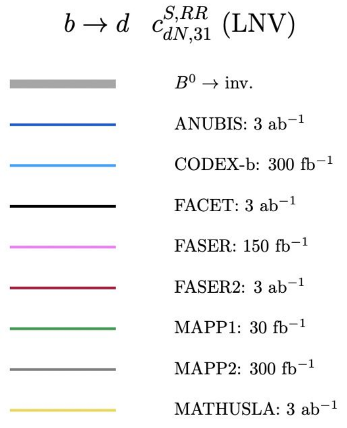
Diagram by R. Beltrán

- More EFT and HNLs!

Example $\mathcal{O}_{dN}^{S,RR}$ | $(\overline{d_L} d_R)\,(\overline{N_R^c} N_R)$

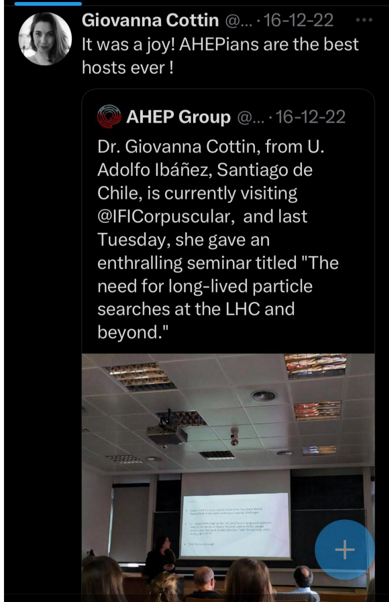
Full simulation (solid lines) in R. Beltrán, et al, JHEP 01 (2023) 015
Reinterpretation (dashed lines) in R. Beltrán, et al, JHEP 05 (2023) 031





$$c \sim 10^{-4} \xrightarrow{c\,\sim 1/\Lambda^3} \Lambda \lesssim \mathcal{O}(10)\ \mathrm{TeV}$$

Giovanna Cottin will visit IFIC from 5th to 21st of December 2022



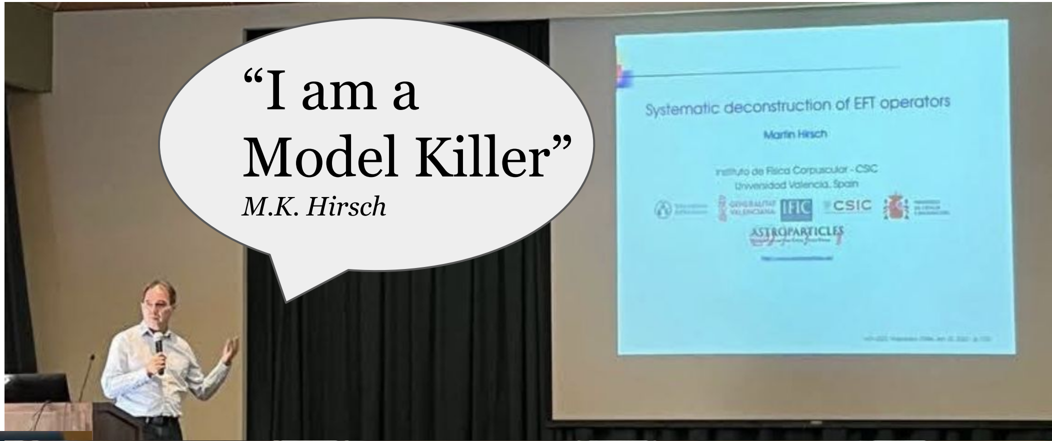
We met again in Santiago !

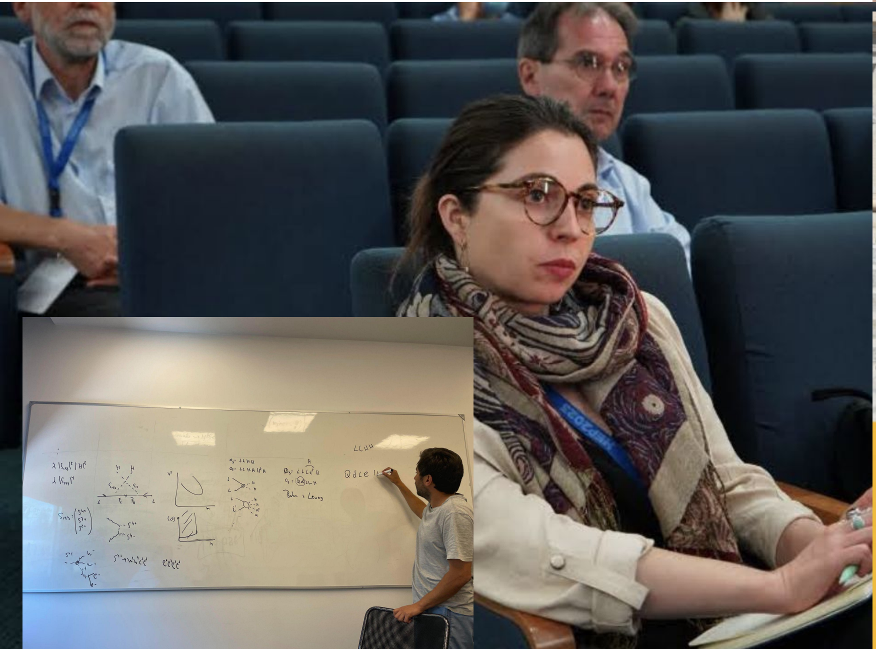
@ Chile 2023

And in Valparaíso !

@ Chile 2023

But again, mostly work !
@HEP2023 and 1st SAPHIR ARM23





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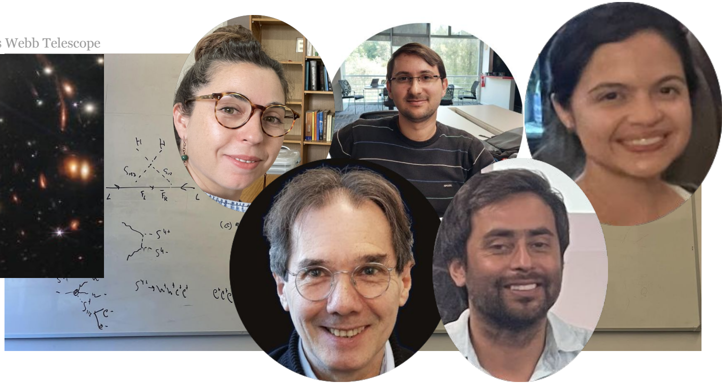
SAPHIR

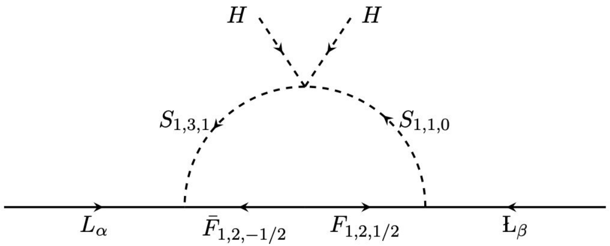
SAPHIR ARM23
Theory meets experiment
La Serena del 18 al 20 de enero

2023 - 2024

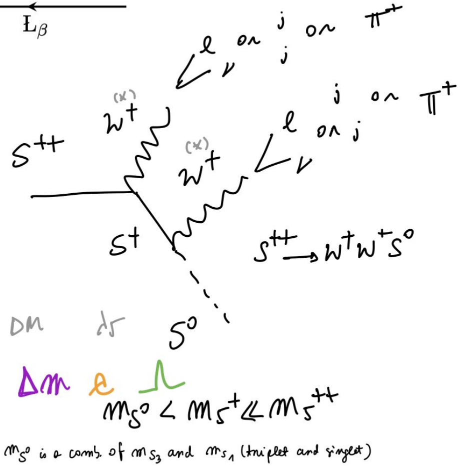
- A new faculty job for me (2023)
- A new project connecting LLPs with neutrino masses and dark matter phenomenology !
- And much more knowledge from Martin

@James Webb Telescope

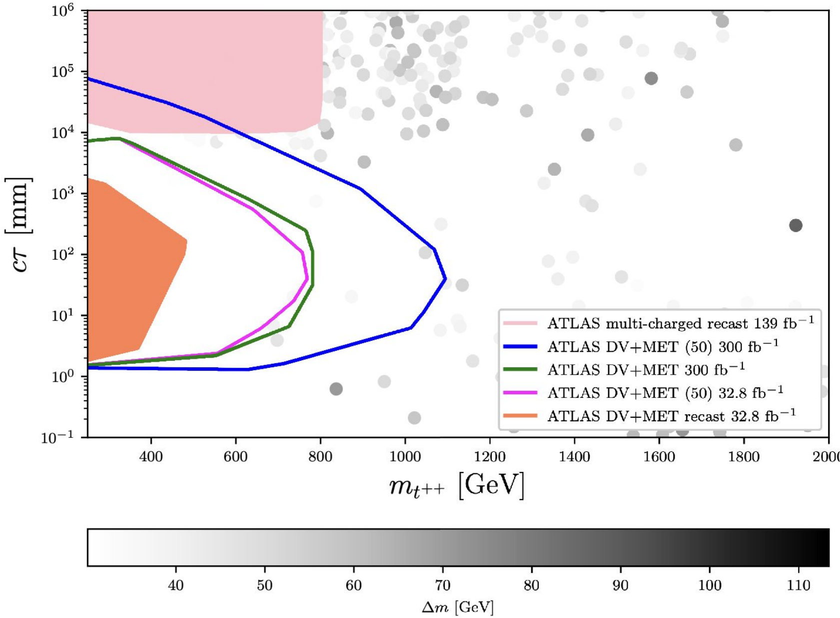




Model from C. Arbeláez, R. Cepedello, J.C. Helo, M. Hirsch and S. Kovalenko, JHEP 08 (2022) 023

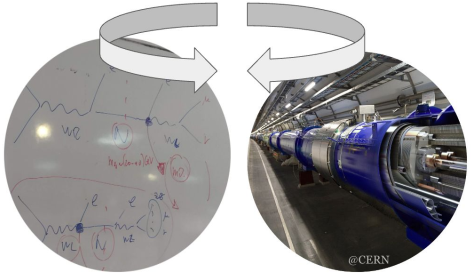


Carolina Arbeláez, Giovanna Cottin, Juan Carlos Helo, Martin Hirsch, Téssio B. de Melo, **IN PROGRESS !**



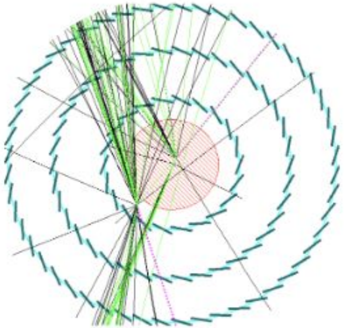
2024 + ?

- 10 papers with 606 citations (~half from LLP whitepaper)
- ~100 zoom hours !
- Not so many sours !
- Hopefully a much longer lived collaboration !
  With cool physics and more fun :-)

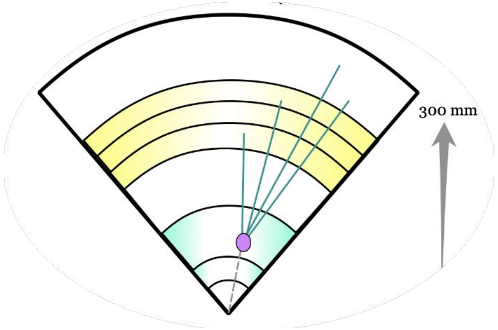


Martin, it is an honor to be your collaborator! Thanks for sharing your **passion for physics**, your knowledge, your **assertiveness**, your laughs, your patience, your **respect**, your wisdom and for making us better scientists !

2018

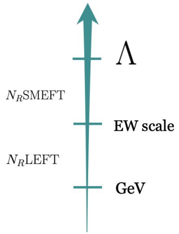


2019-2020



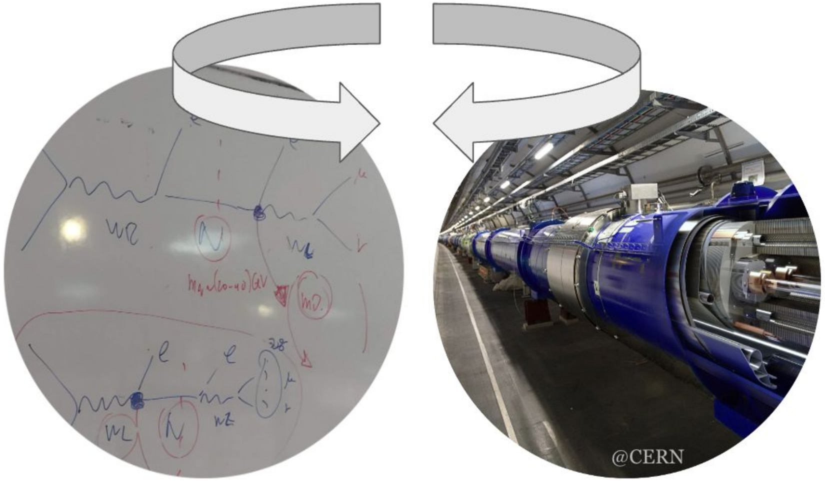
2020-2022

2022 - 2023



2023 - 2024

Backup



Long-lived charged particles and multi-lepton signatures from neutrino mass models

#6

Carolina Arbeláez R (Santa Maria U., Valparaiso and CCTVal, Valparaiso), Giovanna Cottin (Adolfo Ibanez U.), Juan Carlos Helo (La Serena U.), Martin Hirsch (Valencia U., IFIC) (Mar 25, 2020)

Published in: *Phys.Rev.D* 101 (2020) 9, 095033 • e-Print: 2003.11494 [hep-ph]

pdf DOI cite claim reference search 12 citations

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

#7

Juliette Alimena (Ohio State U.), James Beacham (Duke U.), Martino Borsato (Heidelberg U.), Yangyang Cheng (Cornell U., LNS), Xabier Cid Vidal (Santiago de Compostela U.) et al. (Mar 11, 2019)

Published in: *J.Phys.G* 47 (2020) 9, 090501 • e-Print: 1903.04497 [hep-ex]

pdf links DOI cite claim reference search 351 citations

Revisiting the LHC reach in the displaced region of the minimal left-right symmetric model

#8

Giovanna Cottin (Taiwan, Natl. Taiwan U.), Juan Carlos Helo (La Serena U.), Martin Hirsch (Valencia U.), Dario Silva (La Serena U.) (Feb 14, 2019)

Published in: *Phys.Rev.D* 99 (2019) 11, 115013 • e-Print: 1902.05673 [hep-ph]

pdf DOI cite claim reference search 15 citations

Displaced vertices as probes of sterile neutrino mixing at the LHC

#9

Giovanna Cottin (Taiwan, Natl. Taiwan U.), Juan Carlos Helo (La Serena U. and CCTVal, Valparaiso), Martin Hirsch (Valencia U., IFIC) (Jun 13, 2018)

Published in: *Phys.Rev.D* 98 (2018) 3, 035012 • e-Print: 1806.05191 [hep-ph]

pdf DOI cite claim reference search 77 citations

Searches for light sterile neutrinos with multitrack displaced vertices

#10

Giovanna Cottin (Cambridge U. and Taiwan, Natl. Taiwan U.), Juan Carlos Helo (La Serena U. and Valparaiso Ctr. Sci. Tech.), Martin Hirsch (U. Valencia (main)) (Jan 8, 2018)

Published in: *Phys.Rev.D* 97 (2018) 5, 055025 • e-Print: 1801.02734 [hep-ph]

pdf DOI cite claim reference search 70 citations

Reinterpretation of searches for long-lived particles from meson decays #1

Rebeca Beltrán (Valencia U.), Giovanna Cottin (Adolfo Ibanez U. and Chile U., Santiago), Martin Hirsch (Valencia U.), Arsenii Titov (Pisa U. and INFN, Pisa), Zeren Simon Wang (Taiwan, Natl. Tsing Hua U.) (Feb 6, 2023)

Published in: *JHEP* 05 (2023) 031 • e-Print: 2302.03216 [hep-ph]

pdf DOI cite claim reference search 9 citations

Long-lived heavy neutral leptons with a displaced shower signature at CMS #2

Giovanna Cottin (Adolfo Ibanez U. and Chile U., Santiago), Juan Carlos Helo (Chile U., Santiago and La Serena U.), Martin Hirsch (Valencia U.), Cristián Peña (Fermilab), Christina Wang (Caltech) et al. (Oct 31, 2022)

Published in: *JHEP* 02 (2023) 011 • e-Print: 2210.17446 [hep-ph]

pdf links DOI cite claim reference search 6 citations

Long-lived heavy neutral leptons from mesons in effective field theory #3

Rebeca Beltrán (Valencia U.), Giovanna Cottin (Adolfo Ibanez U. and Chile U., Santiago), Juan Carlos Helo (Chile U., Santiago and La Serena U.), Martin Hirsch (Valencia U.), Arsenii Titov (Valencia U., IFIC and Valencia U.) et al. (Oct 5, 2022)

Published in: *JHEP* 01 (2023) 015 • e-Print: 2210.02461 [hep-ph]

pdf DOI cite claim reference search 14 citations

Long-lived heavy neutral leptons at the LHC: four-fermion single-N$_R$ operators #4

Rebeca Beltrán (Valencia U.), Giovanna Cottin (Adolfo Ibanez U. and Chile U., Santiago), Juan Carlos Helo (Chile U., Santiago and La Serena U.), Martin Hirsch (Valencia U.), Arsenii Titov (Valencia U., IFIC and Valencia U.) et al. (Oct 28, 2021)

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Heavy neutral leptons in effective field theory and the high-luminosity LHC #5

Giovanna Cottin (Adolfo Ibanez U.), Juan Carlos Helo (La Serena U.), Martin Hirsch (Valencia U.), Arsenii Titov (Valencia U. and Valencia U., IFIC), Zeren Simon Wang (Taiwan, Natl. Tsing Hua U.) (May 28, 2021)

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PHYSICAL REVIEW D **101,** 095033 (2020)

Long-lived charged particles and multilepton signatures from neutrino mass models

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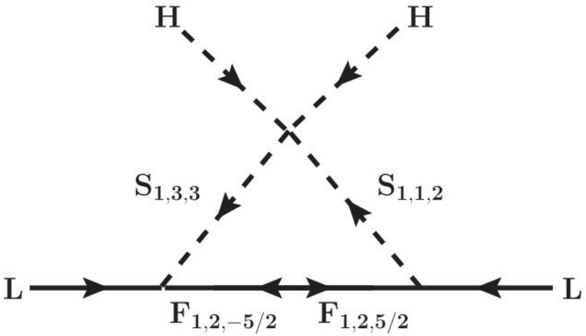
Lepton number violation (LNV) is usually searched for by the LHC collaborations using the same-sign dilepton plus jet signature. In this paper, we discuss multilepton signals of LNV that can arise with experimentally interesting rates in certain loop models of neutrino mass generation. Interestingly, in such models, the observed smallness of the active neutrino masses, together with the high multiplicity of the final states, leads in large parts of the viable parameter space of such models to the prediction of long-lived *charged* particles, which leave highly ionizing tracks in the detectors. We focus on one particular one-loop neutrino mass model in this class and discuss its LHC phenomenology in some detail.

DOI: 10.1103/PhysRevD.101.095033



II. MODEL

For our numerical results, we will concentrate on a specific model variant; the neutrino mass diagram is shown in Fig. 1. The model introduces a vectorlike fermion pair, $(F, \bar{F}) \equiv (F_{1,2,5/2}, F_{1,2,-5/2})$. Here and everywhere else in this paper, subscripts in the gauge basis denote the transformation properties and charge under the SM gauge group in the order $SU(3)_C \times SU(2)_L \times U(1)_Y$. In the numerical implementation, we use three copies of $(F, \bar{F})$, one for each lepton generation. We note, however, that neutrino data could already be explained with just one copy of $(F, \bar{F})$. The model also has two new scalars, $S_1 \equiv S_{1,1,2}$ and $S_3 \equiv S_{1,3,3}$.

The Lagrangian of the model is given by

$$
\begin{aligned}
\mathcal{L} = \mathcal{L}_{\rm SM} &- m_F F\bar{F} - h_{ee} e^c e^c S_1^\dagger - h_F L F S_1^\dagger - h_{\bar{F}} L \bar{F} S_3 \\
&- m_{S_1}^2 |S_1|^2 - m_{S_3}^2 |S_3|^2 + \lambda_2 |H|^2 |S_1|^2 \\
&+ (\lambda_{3a} |H^\dagger H| |S_3^\dagger S_3| + \lambda_{3b} |H S_3 H^\dagger S_3^\dagger|) + \lambda_4 |S_1|^4 \\
&- \lambda_5 H H S_2 S_3^\dagger + (\lambda_{6a} |S_3^\dagger S_3|^2 + \lambda_{6b} |S_3 S_3 S_3^\dagger S_3^\dagger|) \\
&+ \lambda_7 |S_1|^2 |S_3|^2. \qquad (1)
\end{aligned}
$$

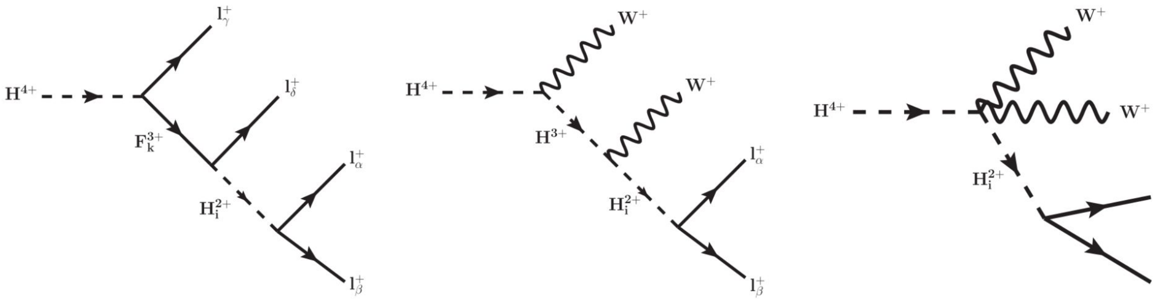


FIG. 2. Feynman diagrams for the decays $H^{4+} \to l_\gamma^+ l_\delta^+ l_\alpha^+ l_\beta^+$ and $H^{4+} \to W^+ W^+ l_\alpha^+ l_\beta^+$.

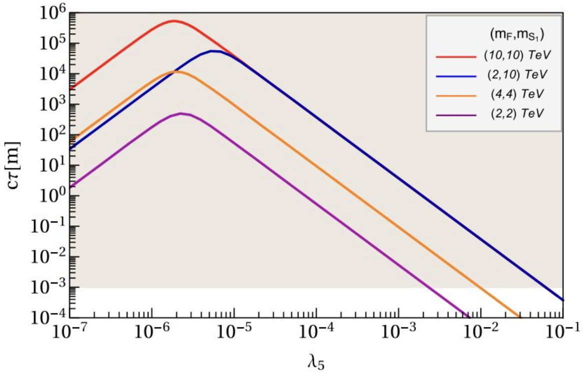
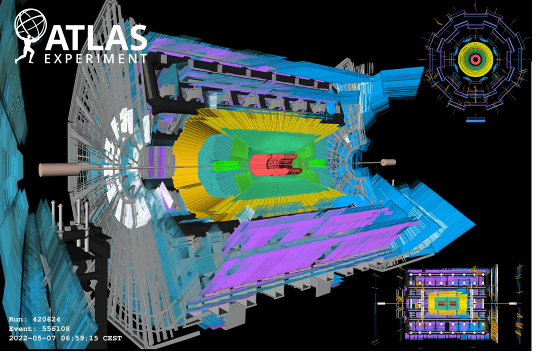


FIG. 3. Decay length of H^{4+} as a function of λ_5, for fixed choices of other parameters. The lightest neutrino mass was fixed to $m_{\nu_1} = 1$ meV; see also the text.

Heavy scalar	$SU(3)_C$	$SU(2)_L$	$U(1)_Y$	Operator	Matching relation
Leptoquark S_d	$\mathbf{3}$	$\mathbf{1}$	$-1/3$	$\mathcal{O}_{duNe}$	$\frac{c_{duNe}}{\Lambda^2} = \frac{g_{dN} g_{ue}}{2m_{S_d}^2}$
Leptoquark S_Q	$\mathbf{3}$	$\mathbf{2}$	$1/6$	$\mathcal{O}_{LdQN}$	$\frac{c_{LdQN}}{\Lambda^2} = \frac{g_{dL} g_{QN}}{m_{S_Q}^2}$
Inert doublet Φ	$\mathbf{1}$	$\mathbf{2}$	$1/2$	$\mathcal{O}_{LNQd}$	$\frac{c_{LNQd}}{\Lambda^2} = \frac{g_{LN} g_{Qd}}{m_{\Phi}^2}$
				$\mathcal{O}_{QuNL}$	$\frac{c_{QuNL}}{\Lambda^2} = \frac{g_{Qu} g_{LN}}{m_{\Phi}^2}$

Table 2. Heavy scalars with their gauge quantum numbers and the four-fermion single-N_R operators they can generate. The last column reports the tree-level matching relations between the Wilson coefficients and the couplings of the UV model.



Standard

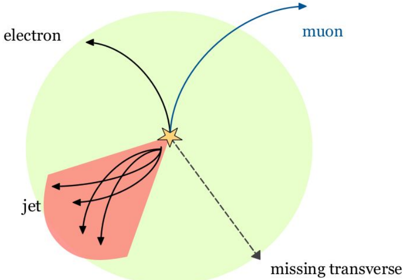
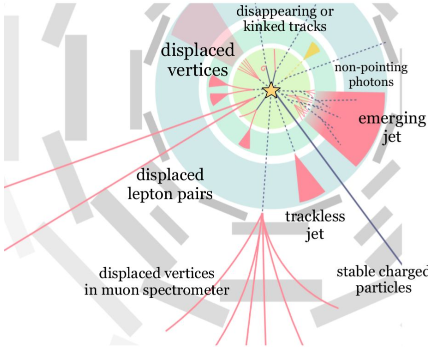


Image by G. Cottin

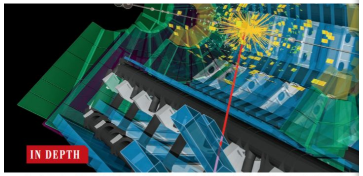
Exotic

Long-lived Particle Community, J. Alimena, **G. Cottin**, et al, [J.Phys.G 47 (2020) 9, 090501]



LLP Image adapted from Heather Russel

Science (2019), IOP (2023)



IN DEPTH

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 the Higgs boson, the last particle predicted 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 the existence of long-lived particles," she 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 people have written, basically rejects these

New physics "X" at colliders

most LHC searches here

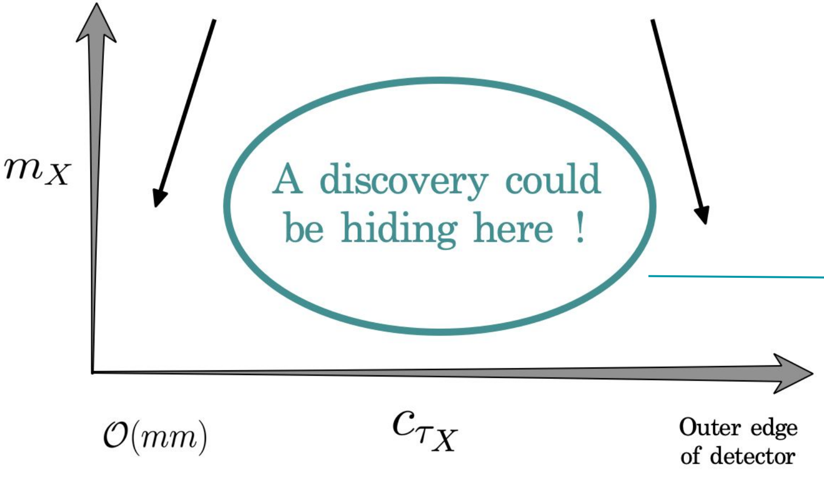
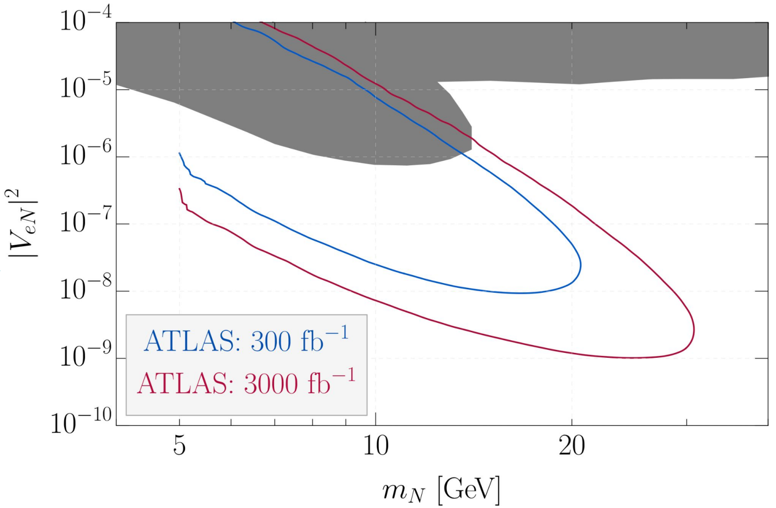


Image by G. Cottin reproduced from J. Beacham

HNL DV Strategy first proposed in **G. Cottin**, J.C. Helo and M. Hirsch, [PRD 98 (2018)]

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



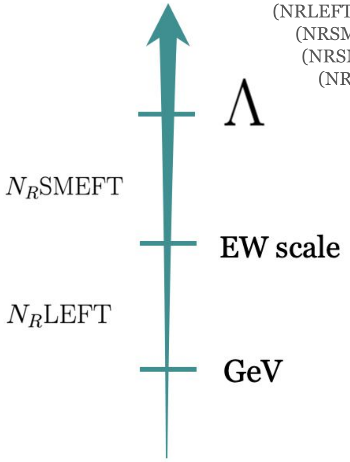
Beyond Minimal HNL

HNL production occurs via meson decays for $m_N < 5$ GeV

We can study them systematically in an EFT approach

$$\mathcal{L}_{N_R\text{LEFT}} = \mathcal{L}_{\text{ren}} + \sum_{d\geq 5}\sum_i c_i^{(d)}\mathcal{O}_i^{(d)}$$

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, single N) G. Cottin, et al, JHEP 09 (2021)
(NRSMEFT, pair N) R. Beltrán, et al, JHEP 01 (2022)
(NRLEFT, pair N) R. Beltrán, et al, JHEP 01 (2023)



F. del Aguila, et al, Phys.Lett.B 670 (2009)
A. Aparici, et al, Phys.Rev.D 80 (2009)
Y. Liao, et al, Phys.Rev.D 96 (2017)

T. Li, et al, JHEP 07 (2020) 152
M. Chala, A. Titov, JHEP 05 (2020) 139

Meson decay via operator, i.e $B^+ \to \pi^+ N N$

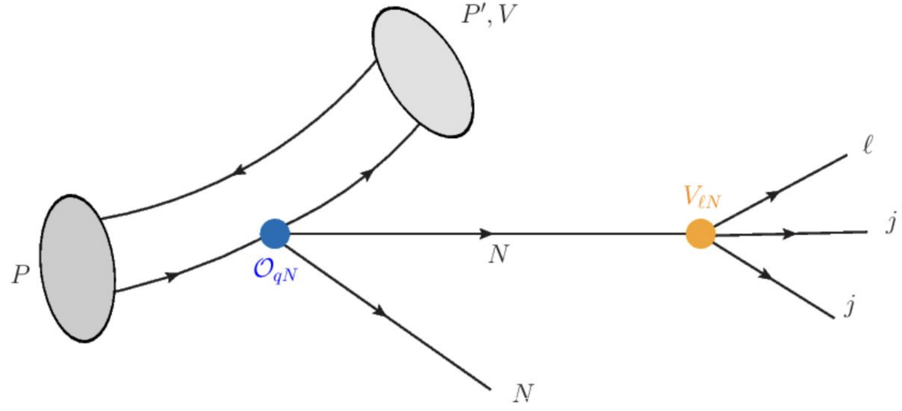


Diagram by R. Beltrán

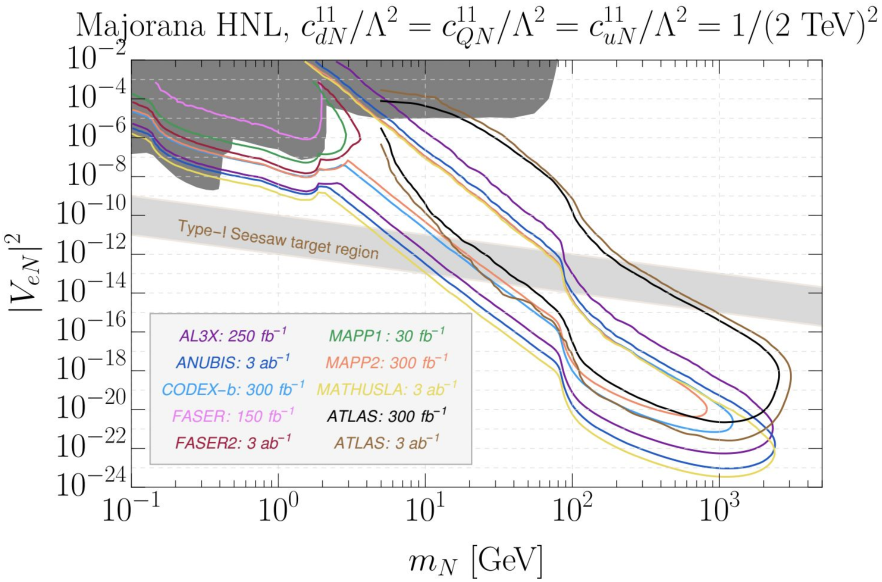
HNL decays via mixing in K. Bondarenko, et al, JHEP 11 (2018) 032

	$2-\text{body}$	$P \to P'$	$P \to V$
$c \to u$	D^0	$D^0 \to \pi^0,\ \eta,\ \eta'$ $D^+ \to \pi^+$ $D_s^+ \to K^+$	$D^0 \to \rho^0,\ \omega$ $D^+ \to \rho^+$ $D_s^+ \to K^{\star +}$
$b \to d$	B^0	$B^0 \to \pi^0,\ \eta,\ \eta'$ $B^+ \to \pi^+$ $B_s^0 \to \overline{K^0}$	$B^0 \to \rho^0,\ \omega$ $B^+ \to \rho^+$ $B_s^0 \to \overline{K^{\star 0}}$
$b \to s$	B_s^0	$B_s^0 \to \eta,\ \eta'$ $B^0 \to K^0$ $B^+ \to K^+$	$B_s^0 \to \phi$ $B^0 \to K^{\star 0}$ $B^+ \to K^{\star +}$

For operators with *pairs* of HNL

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

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



Reinterpretation method

R. Beltrán, G. Cottin, M. Hirsch, A. Titov, Z. S. Wang, JHEP 05 (2023) 031, arXiv:2302.03216

limits from minimal HNL

$$(m_N, |V_{eN}|^2, N_S)$$

Full Monte Carlo simulation (compute decay probabilities at each detector)

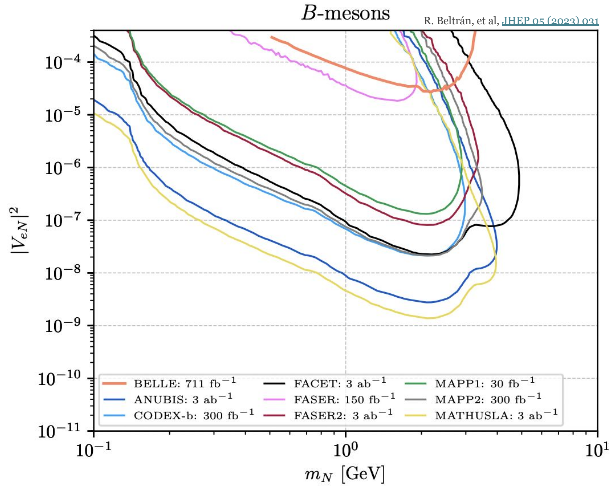
LLP produced from same (or similar) meson *D/B*
lab-frame decay lenght >> distance from IP to detector

reinterpreted limits in EFT (HNL/ALP)

$$(m_N, c, N_S)'/(m_a, c_{ee}, N_S) \quad \Gamma'_{\text{vis.}} \approx \Gamma_{\text{vis.}} \cdot \frac{N_N}{N'_N}\frac{N'_S}{N_S}$$

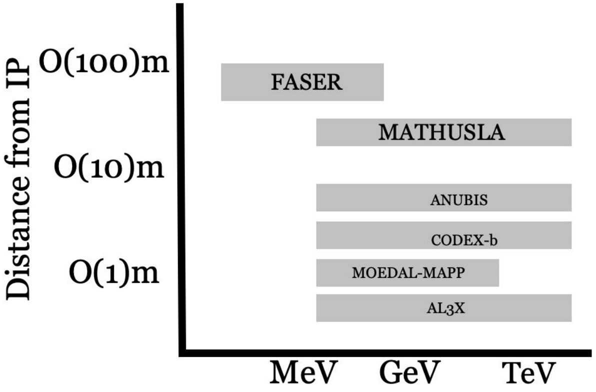
Only theoretical input (LLP production and decay)

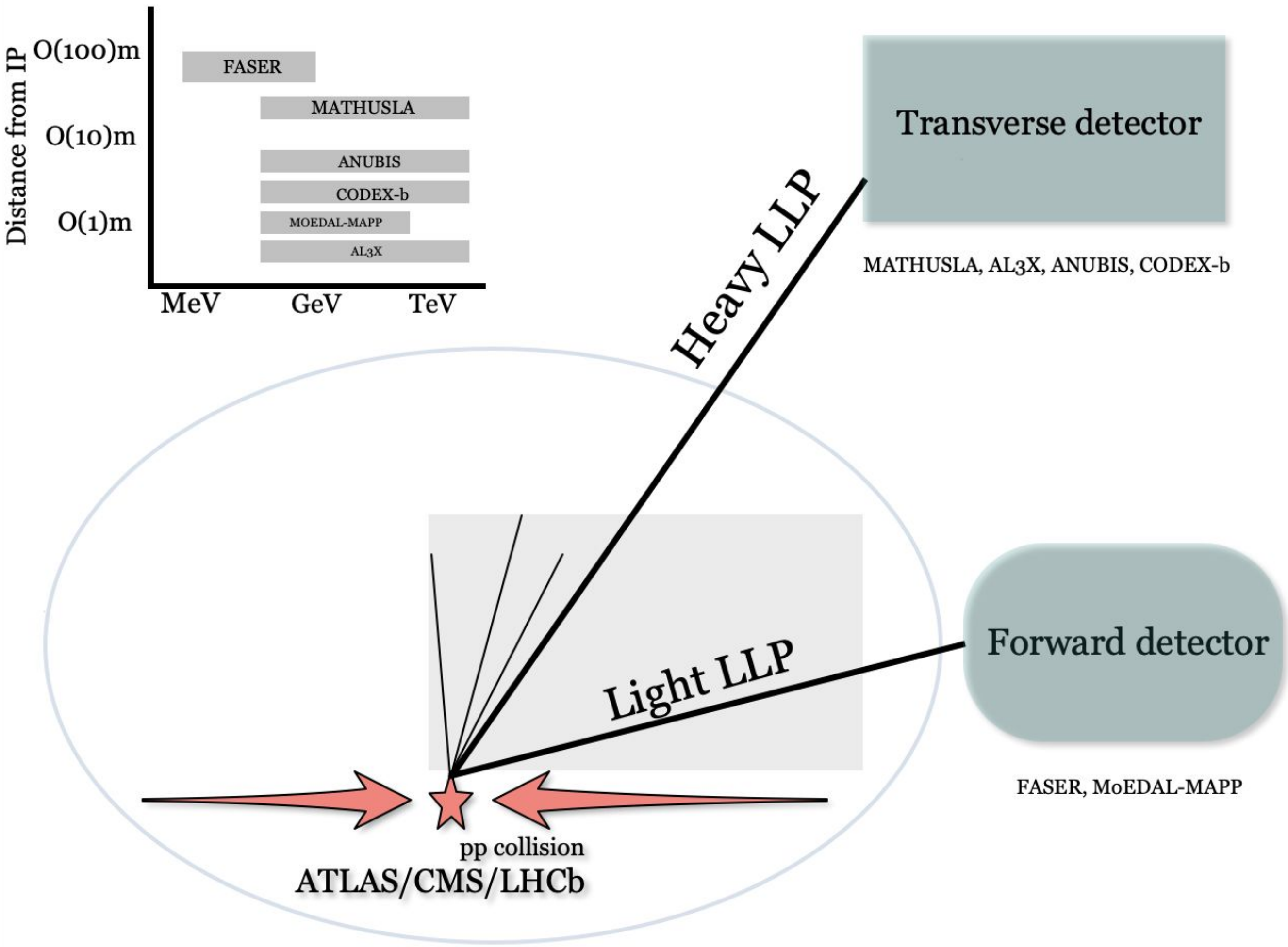
$$N_S = N_N \cdot \epsilon \cdot \text{BR}(N \to \text{vis.})$$



$$P[\text{decay}] \approx \Delta L/\lambda_{\text{decay}} = \Delta L \cdot \Gamma_{\text{tot.}}/(\beta\gamma c\hbar)$$

$$N_S = N_N \cdot \Gamma_{\text{tot.}} \cdot \text{BR}(N \to \text{vis.}) \sim N_N \cdot \Gamma_{\text{vis.}}$$





Distance from IP
O(100)m
O(10)m
O(1)m
FASER
MATHUSLA
ANUBIS
CODEX-b
MOEDAL-MAPP
AL3X
MeV
GeV
TeV
Transverse detector
MATHUSLA, AL3X, ANUBIS, CODEX-b
Heavy LLP
Light LLP
Forward detector
FASER, MoEDAL-MAPP
pp collision
ATLAS/CMS/LHCb