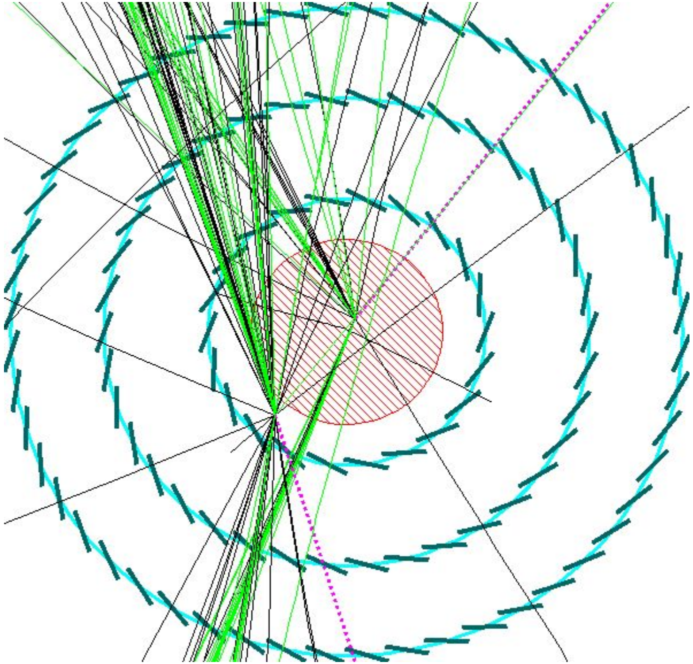
國立臺灣大學
National Taiwan University

Theory/Pheno Overview of Long-Lived Particles



Giovanna Cottin

Workshop on New Physics with Displaced Vertices
NCTS, Taiwan
June 2018

Outline

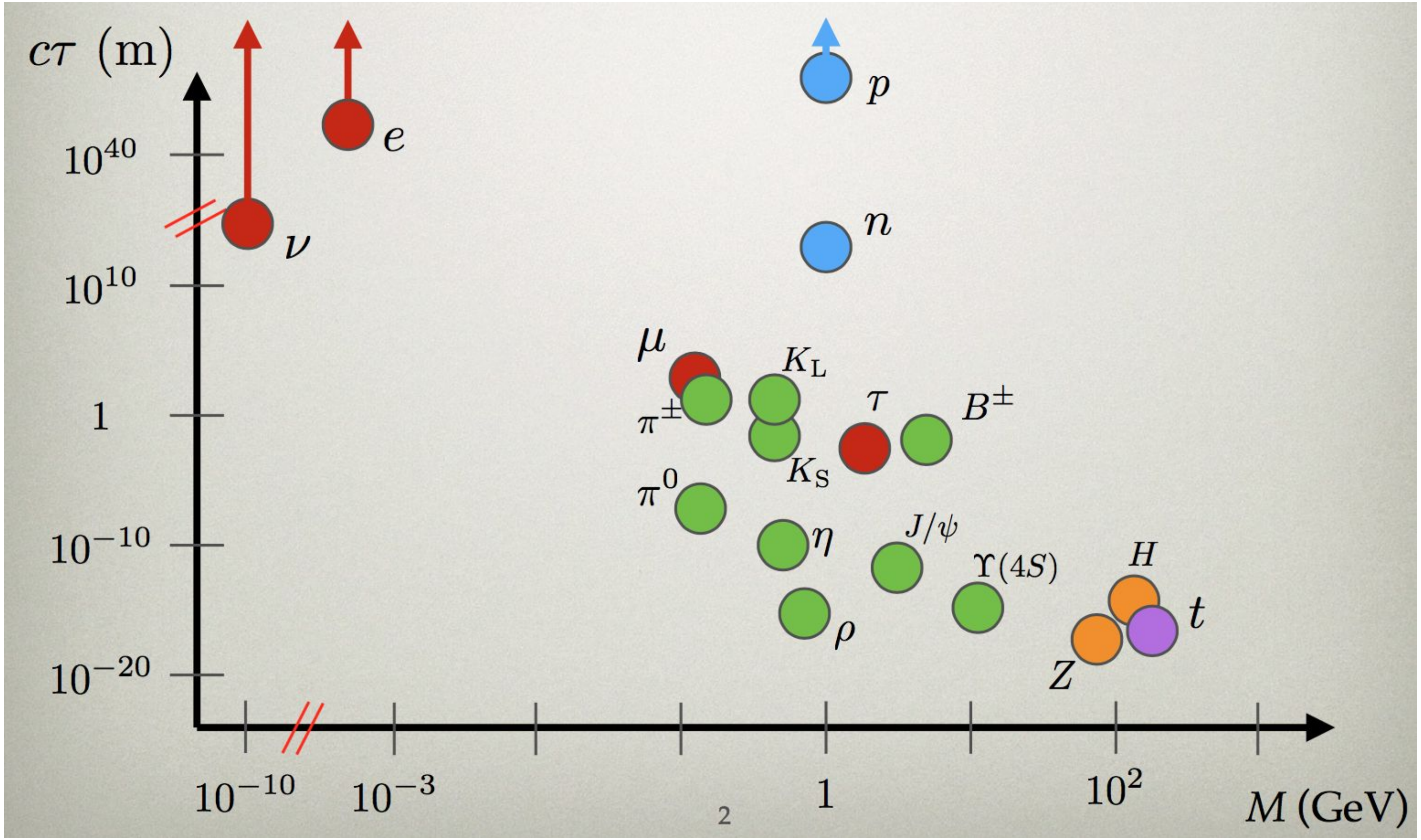
Motivation: Importance of Long-Lived Particles (LLPs) in BSM theories

Examples of Models with LLPs

LLPs at the LHC : The need to search for non-standard signatures

Mapping the Lifetime Frontier

The SM is full of long-lived particles (LLPs)

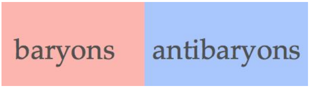


Their presence comes from conserved symmetries, small couplings or heavy mediators

Source: [B.Shuve @ LHC-LLP workshop, CERN]

From now on : **LLP = BSM particle that dies (gives up all its energy or decays to SM) somewhere in the detector acceptance.** [J.Beachman @ LHC-LLP workshop, CERN]

Importance of LLPs beyond the SM:
We need BSM physics ...



Source: wikipedia.org, nobelprize.org

Motivation

Particle Dark Matter
Baryogenesis
Neutrino Masses
Naturalness

Theory

SUSY (RPV, mini-split)
Higgs Portal (Hidden Valley/Neutral Naturalness)
Gauge Portal (Z', dark photon)
Dark Matter (EWK Multiplets, SIMPs)
RH Neutrinos (nuMSM, Left-Right Symmetry)

Phenomenology

LLPs/ signatures

Experiment

Data

.. to explain naturalness, baryogenesis, dark matter and neutrino masses. We need to **invest** in a dedicated long-lived particle (LLP) program at colliders/experiments

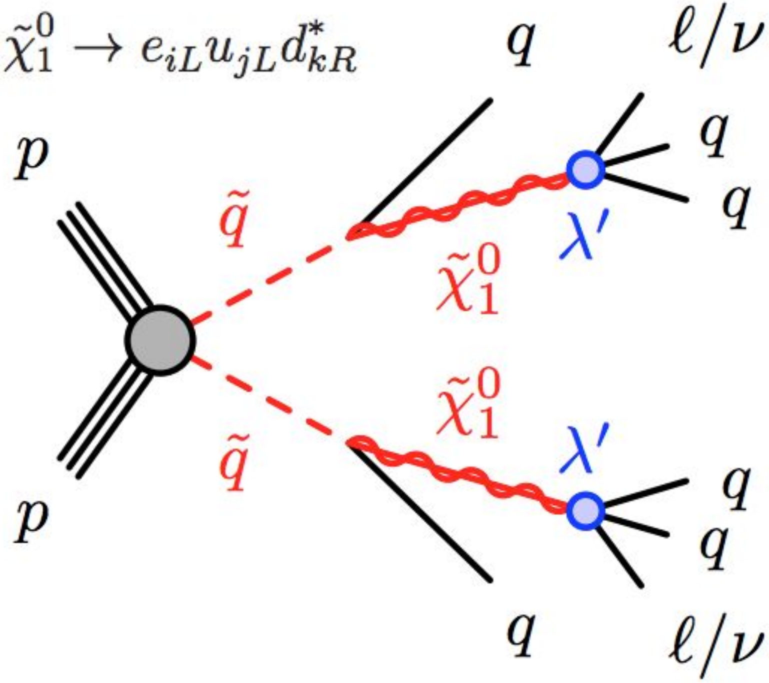
Examples of New Physics Models with Long-Lived Particles

Supersymmetry : R-parity violating SUSY

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

$$\hat{W}_{\mathrm{RpV}} = \varepsilon_{ab}[\epsilon_i \hat{L}_i^a \hat{H}_u^b + \lambda_{ijk} \hat{L}_i^a \hat{L}_j^b \hat{E}_k + \lambda'_{ijk} \hat{L}_i^a \hat{Q}_j^b \hat{D}_k] + \lambda''_{ijk} \hat{U}_i \hat{D}_j \hat{D}_k$$

$$\tilde{\chi}_1^0 \to e_{iL} u_{jL} d_{kR}^*$$



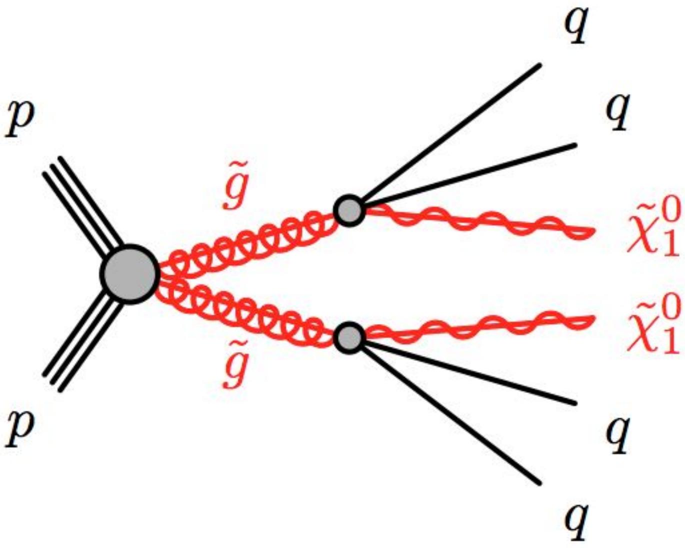
$$c\tau \simeq \frac{3}{\lambda'^2_{ijk}} \left(\frac{m_{\tilde{f}}}{100\ \mathrm{GeV}}\right)^4 \left(\frac{1\ \mathrm{GeV}}{m_{\tilde{\chi}_1^0}}\right)^5 \mathrm{mm}$$

Small couplings give rise to macroscopic neutralino lifetime

Supersymmetry : split SUSY

Split SUSY:
N. Arkani-Hamed and S. Dimopoulos, , JHEP 0506 (2005) 073
G. Giudice and A. Romanino, Nucl.Phys. B699 (2004)

Heavy SUSY scalars



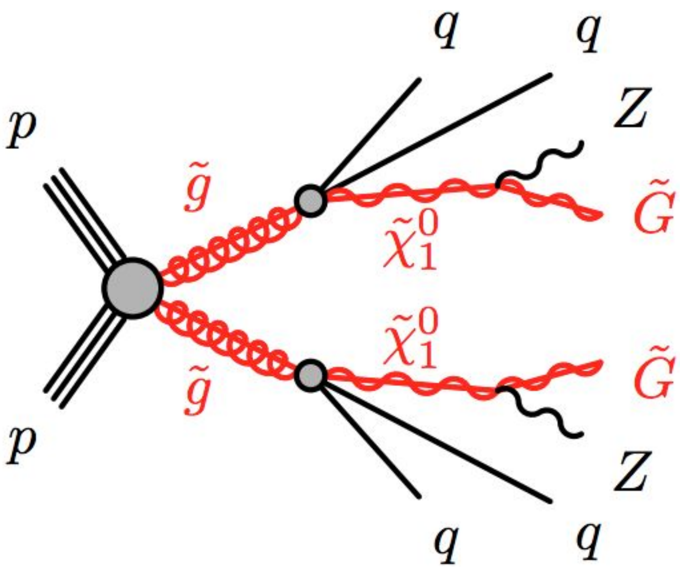
$$c\tau \simeq 2 \times 10^{-1} \left(\frac{2\ \mathrm{TeV}}{M_3}\right)^5 \left(\frac{\tilde{m}}{10^6\ \mathrm{GeV}}\right)^4 \mathrm{mm}$$

Decay via highly off-shell squarks leads to long-lived gluino

Displaced gluinos in:
P. Gambino, G. Giudice and P. Slavich, Nucl.Phys. B726 (2005)

Supersymmetry : Gauge Mediation

GGM:
G. F. Giudice and R. Rattazzi, Phys. Rept. 322 (1999)



$$c\tau \simeq 130 \left(\frac{100\ \mathrm{GeV}}{m_{\tilde{\chi}_1^0}}\right)^5 \left(\frac{\sqrt{F}}{100\ \mathrm{TeV}}\right)^4 \times 10^{-3}\ \mathrm{mm}$$

Decays to gravitino suppressed by SUSY-breaking scale

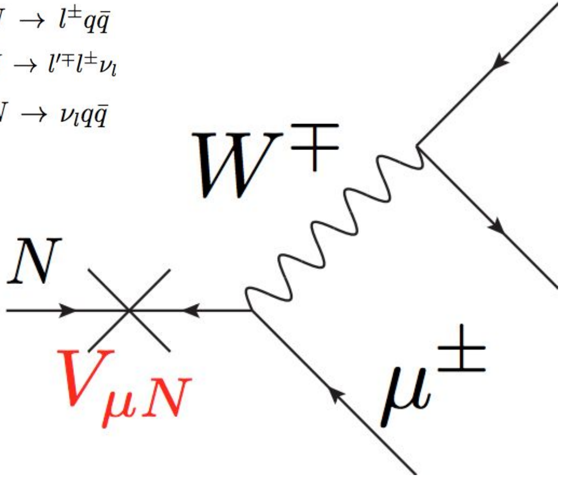
Some displaced GGM studies in:
B.C. Allanach, M. Badziak, G. Cottin, N. Desai, C. Hugonie, R. Ziegler, Eur.Phys.J. C76 (2016)
A. Delgado, G. F. Giudice, P. Slavic, Phys. Lett. B653 (2007)

Sterile Neutrinos : Standard Model + N

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)

$$pp \to W^{\pm} \to Nl^{\pm}$$

$$N \to l^{\pm} q\bar{q}$$
$$N \to l'^{\mp} l^{\pm} \nu_l$$
$$N \to \nu_l q\bar{q}$$



$$c\tau_N \sim 3.7 \left(\frac{1\,\mathrm{GeV}}{m_N}\right)^5 \left(\frac{0.1}{|V_{lN}|^2}\right) \ [\mathrm{mm}]$$

Sterile N mixes with SM neutrino.
Large lifetime due to off-shell decay

See also Hiroyuki Ishida and Xing-Bo Yuan's talks !

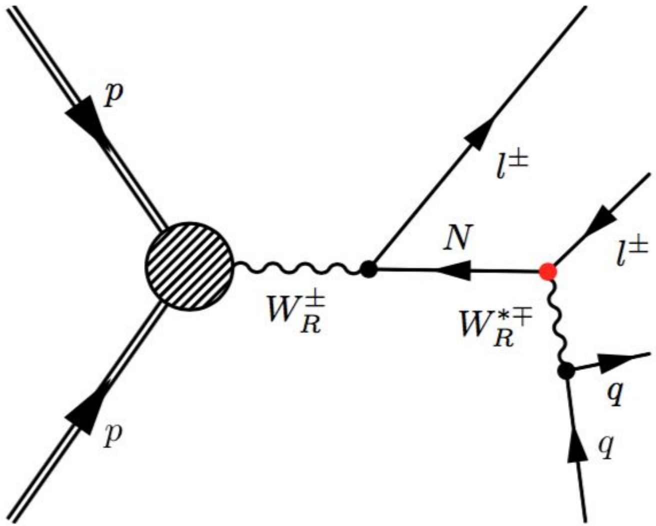
Some displaced N studies in:
G. Cottin, J.C. Helo and M. Hirsch, arXiv:1806.05191
E. Izaguirre and B. Shuve, Phys. Rev. D91 (2015)
S. Dube, D. Gadkari, and A. M. Thalapillil, Phys. Rev. D96 (2017)
J. C. Helo, M. Hirsch, and S. Kovalenko, Phys. Rev. D89 (2014)

Sterile Neutrinos : Left-Right Symmetric model

LR model:

J. C. Pati and A. Salam, Phys. Rev. D10, 275 (1974)
R. N. Mohapatra and J. C. Pati, Phys. Rev. D11, 2558 (1975)
R. N. Mohapatra and G. Senjanovic, Phys. Rev. D23, 165 (1981)

$$SU(2)_L \times SU(2)_R \times U(1)_{B-L}$$

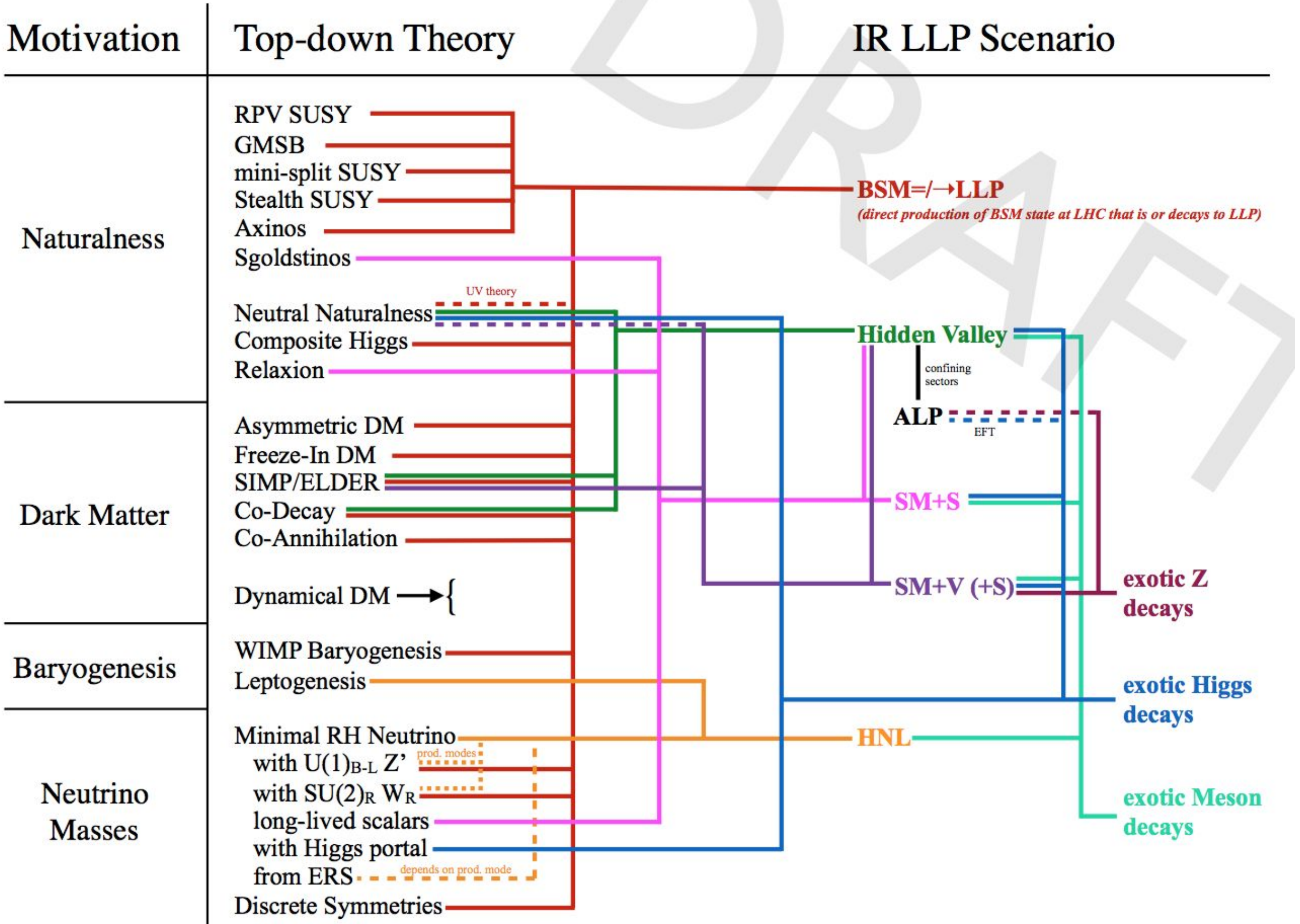


$$c\tau_N \sim 0.12 \left(\frac{10\ \mathrm{GeV}}{m_N}\right)^5 \left(\frac{m_{W_R}}{1000\ \mathrm{GeV}}\right)^4 \quad [\mathrm{mm}]$$

Production and decay of the sterile neutrino depends on the unknown mass of the new, heavy right-handed gauge boson

Some displaced LR studies in:
G. Cottin, J.C. Helo and M. Hirsch, Phys. Rev. D 97 (2018)
M. Nemevsek, F. Nesti, and G. Popara, arXiv:1801.05813
J. C. Helo, M. Hirsch, and S. Kovalenko, Phys. Rev. D89 (2014)

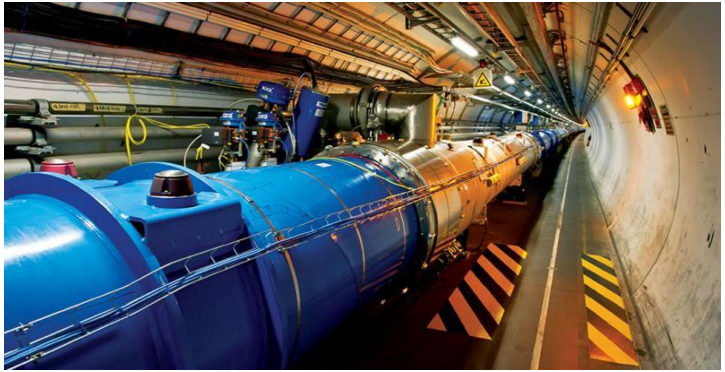
Slide from David Curtin @ May LLP Workshop, CERN



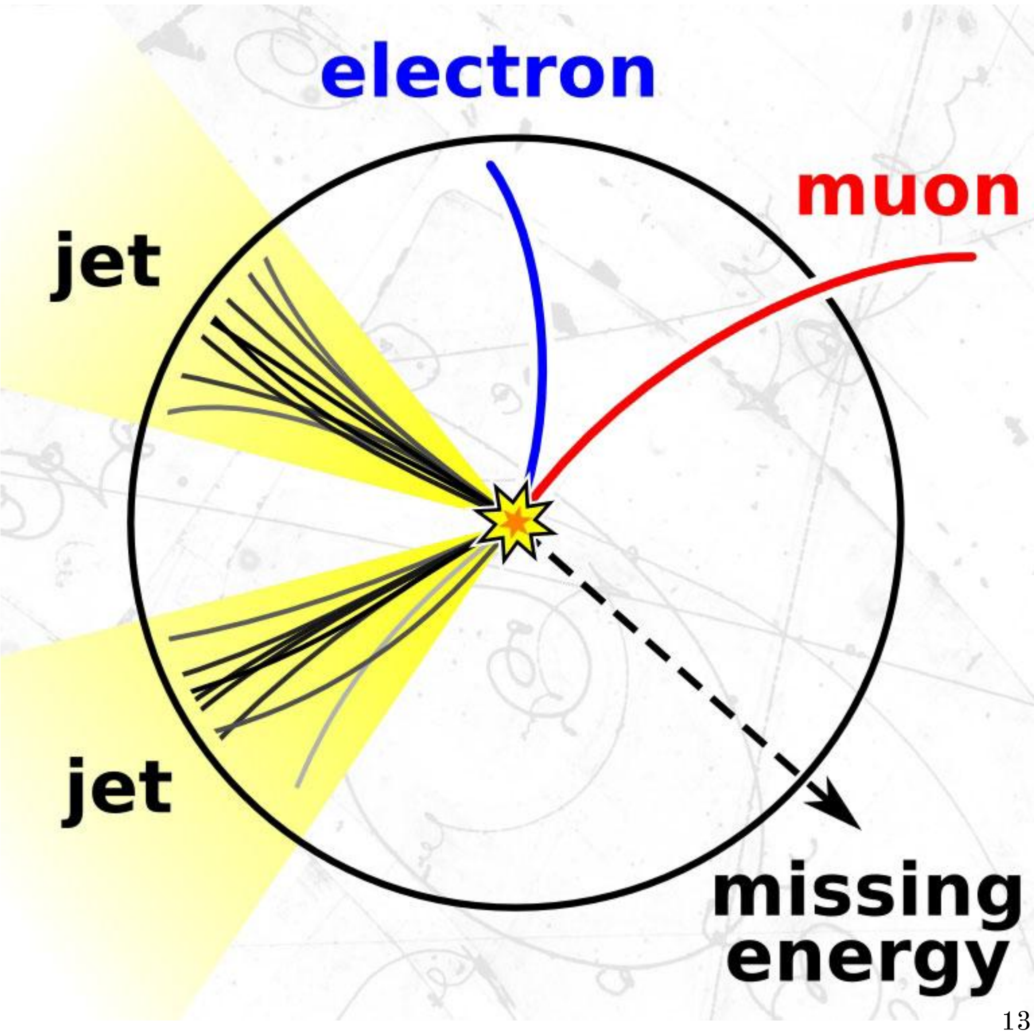
See also M. C. Chu, P. Q. Hung, H. M. Lee, M. Spinrath, S. Sun, Y. Tsai and Sming 's talk !

How do we look for all of this new physics at colliders ?

Standard Signatures @ LHC detectors

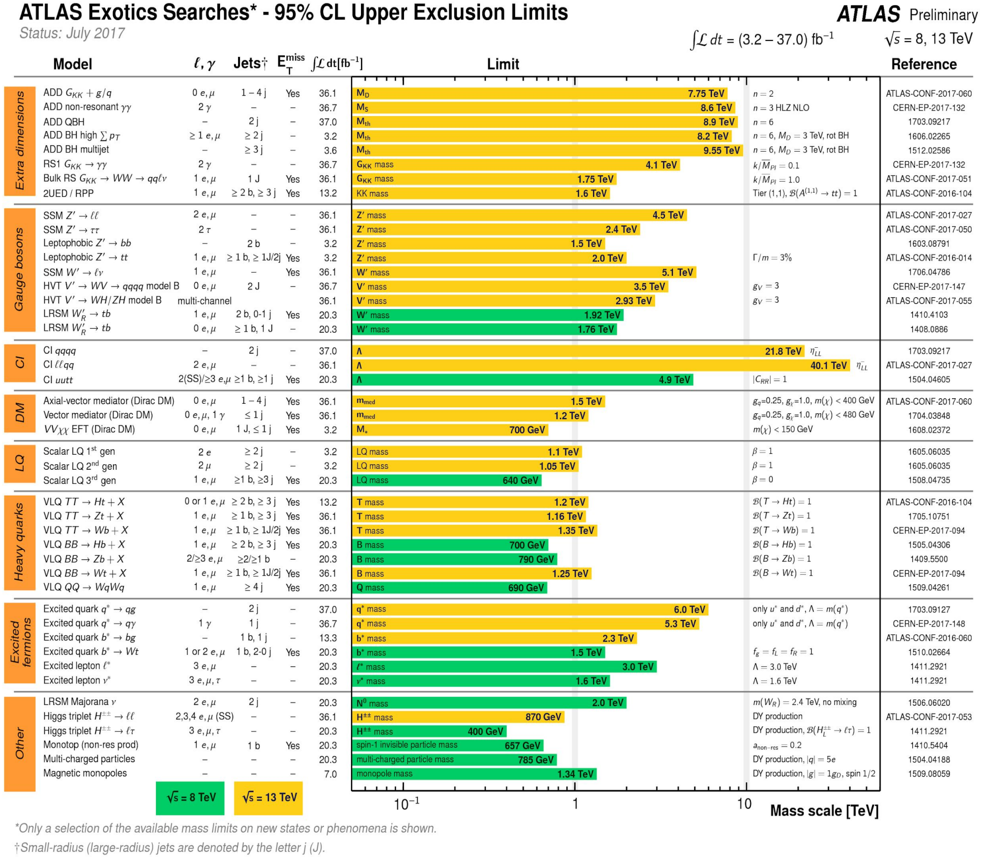


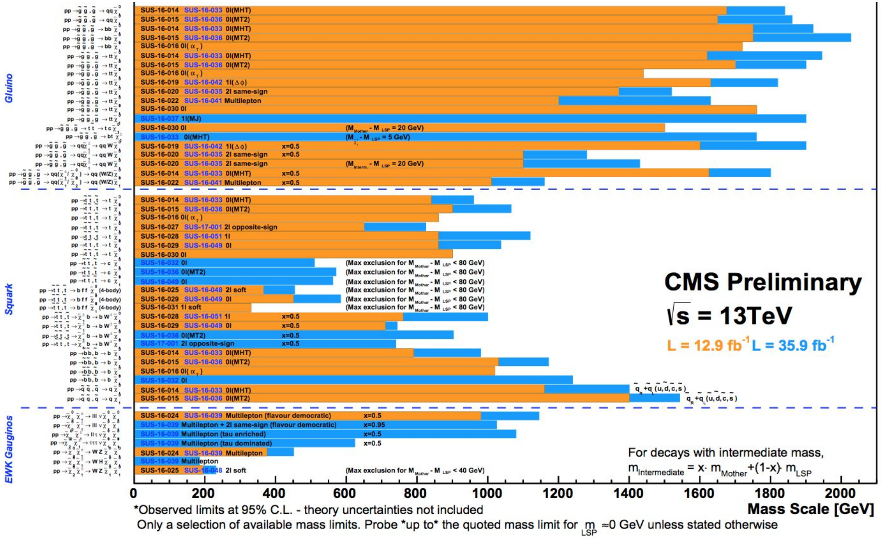
Source: CERN https://home.cern/topics/large-hadron-collider



Source : http://www.fnal.gov/pub/today/images/images11/CMSResult042211figure1.jpg

BUT sadly, no signs of BSM



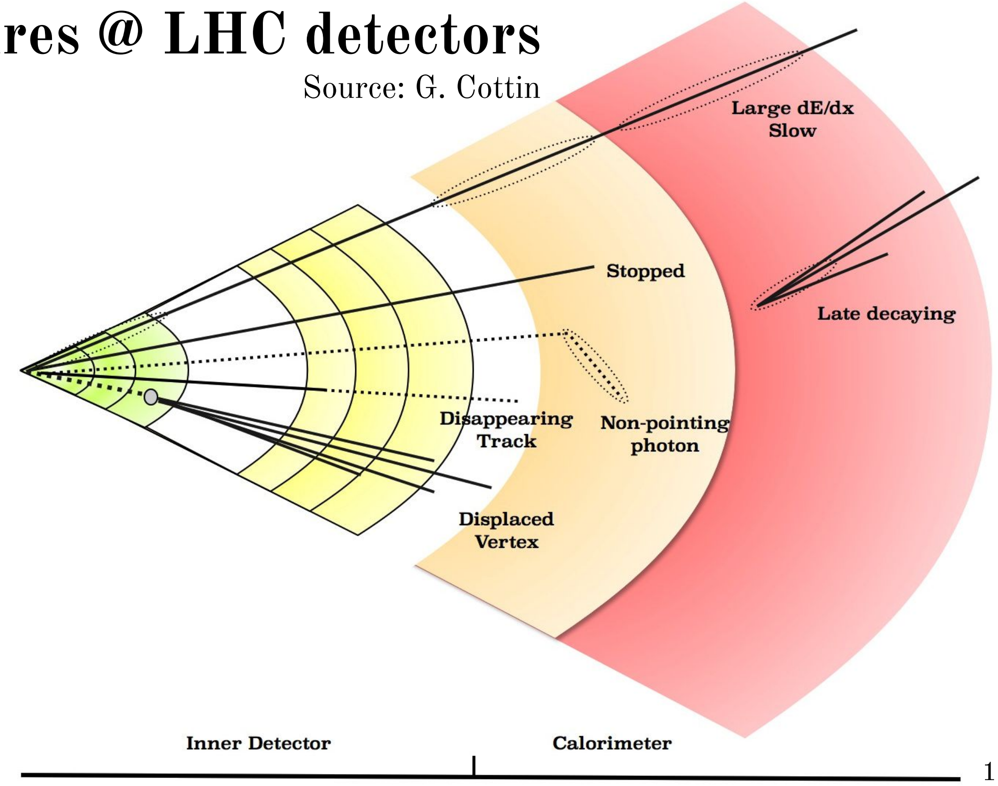


Source : https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CombinedSummaryPlots/EXOTICS/
https://twiki.cern.ch/twiki/pub/CMSPublic/PhysicsResultsSUS/Moriond2017_BarPlot.pdf

We need to push our LHC detectors to look in all places to reduce the chance we will miss new physics !

Long-Lived Particle Signatures @ LHC detectors

Source: G. Cottin

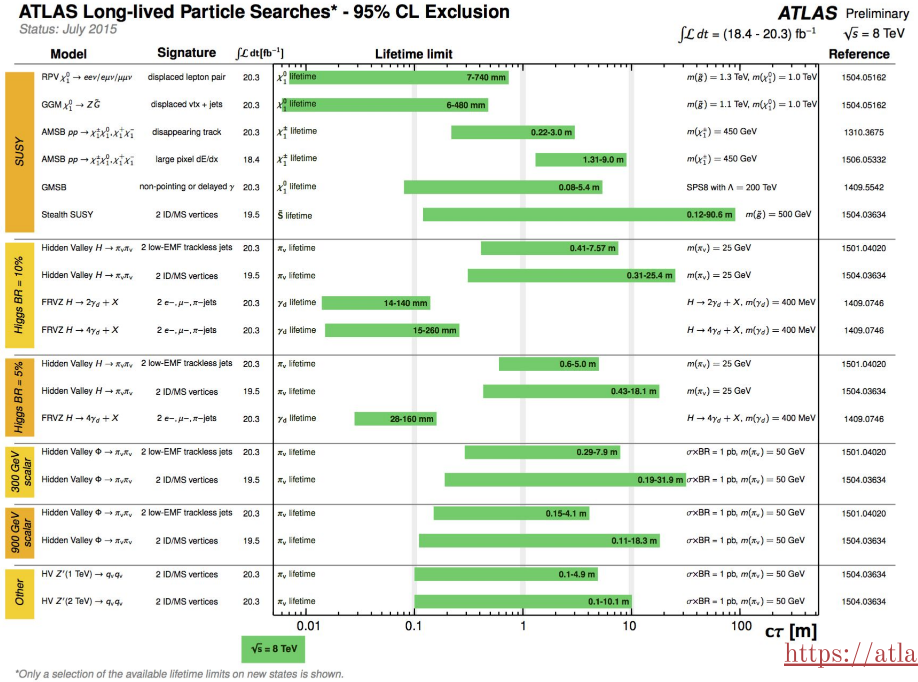


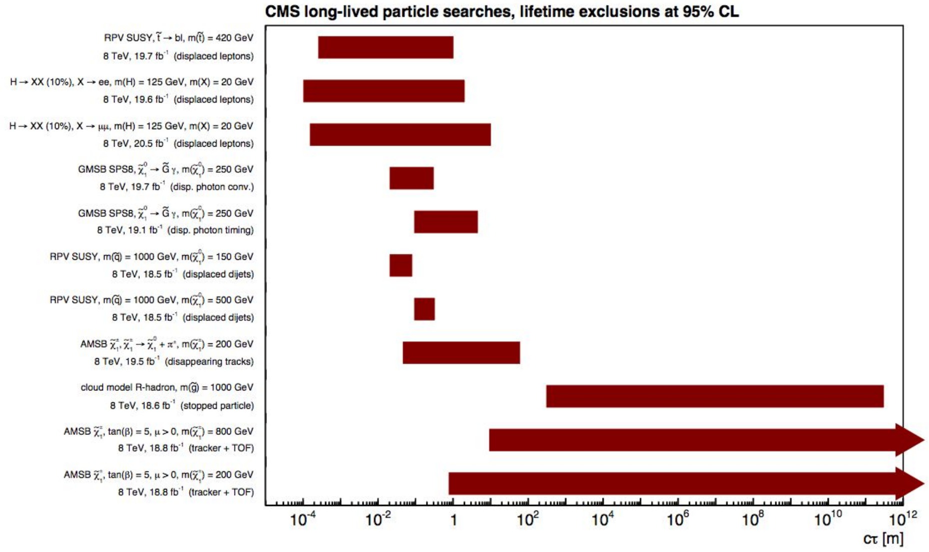
Searches can target specific lifetimes using different parts of the detector. See James Beacham, Shieh-Chieh Hsu, Alberto Belloni and Yanjun Tu's talks !

Detection usually requires **special triggers and reconstruction.** Very **CHALLENGING SEARCHES**

See also Bob Hirosky and Hideyuki Oide's talk !

BUT sadly, ALSO no signs of new physics





Source: https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsEXO
https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CombinedSummaryPlots/EXOTICS

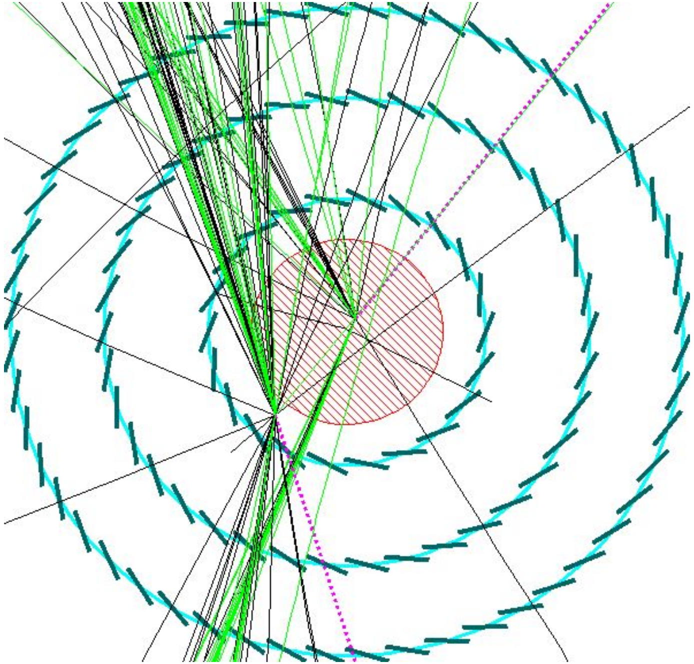
Need to EXTEND and SYSTEMIZE the LLP search program

Aim to search for LLPs in the most generic possible way

See James Beacham's talk !

The lifetime frontier is theoretically and *also* experimentally well motivated

Displaced Vertex signatures @ LHC detectors
Source: G. Cottin



LLPs present in all BSM frameworks

The lack of evidence of new physics at the LHC motivates unconventional searches, such as displaced vertices arising from the decay of a LLP

The null results at the LHC may point that the new physics is so feebly coupled to our SM that its signatures may have been overlooked or misidentified by searches not dedicated to LLPs

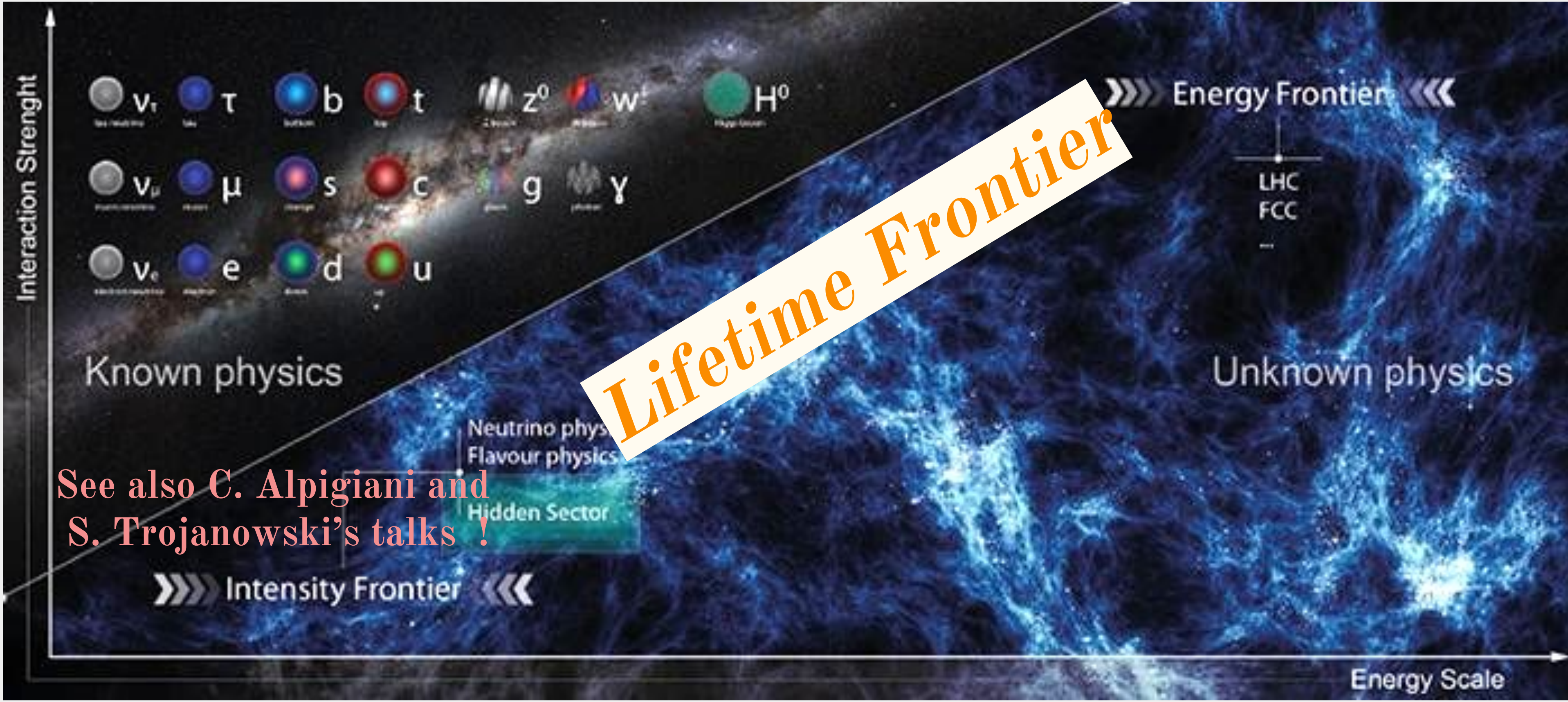


Image credit: Richard Jacobsson and Daniel Dominguez. Source : http://cerncourier.com/cws/article/cern/63982