

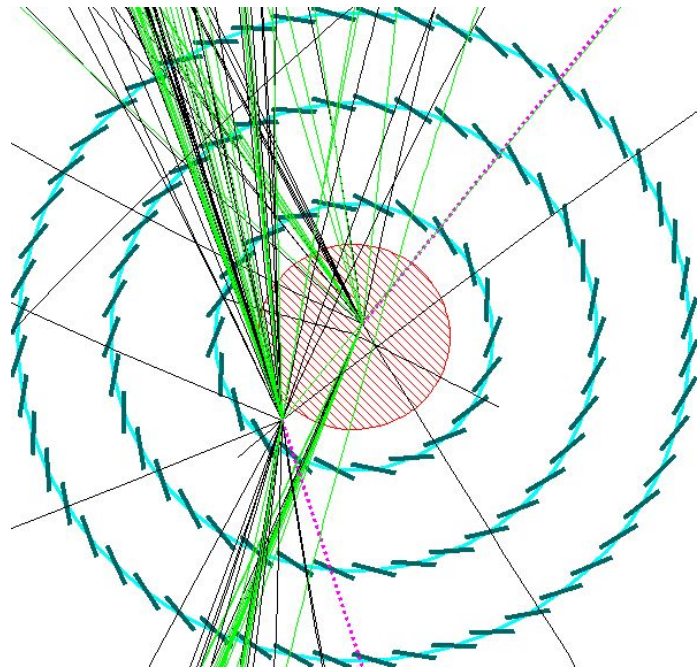


國立臺灣大學
National Taiwan University

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

»»» Energy Frontier «««

LHC
FCC
...

Known physics

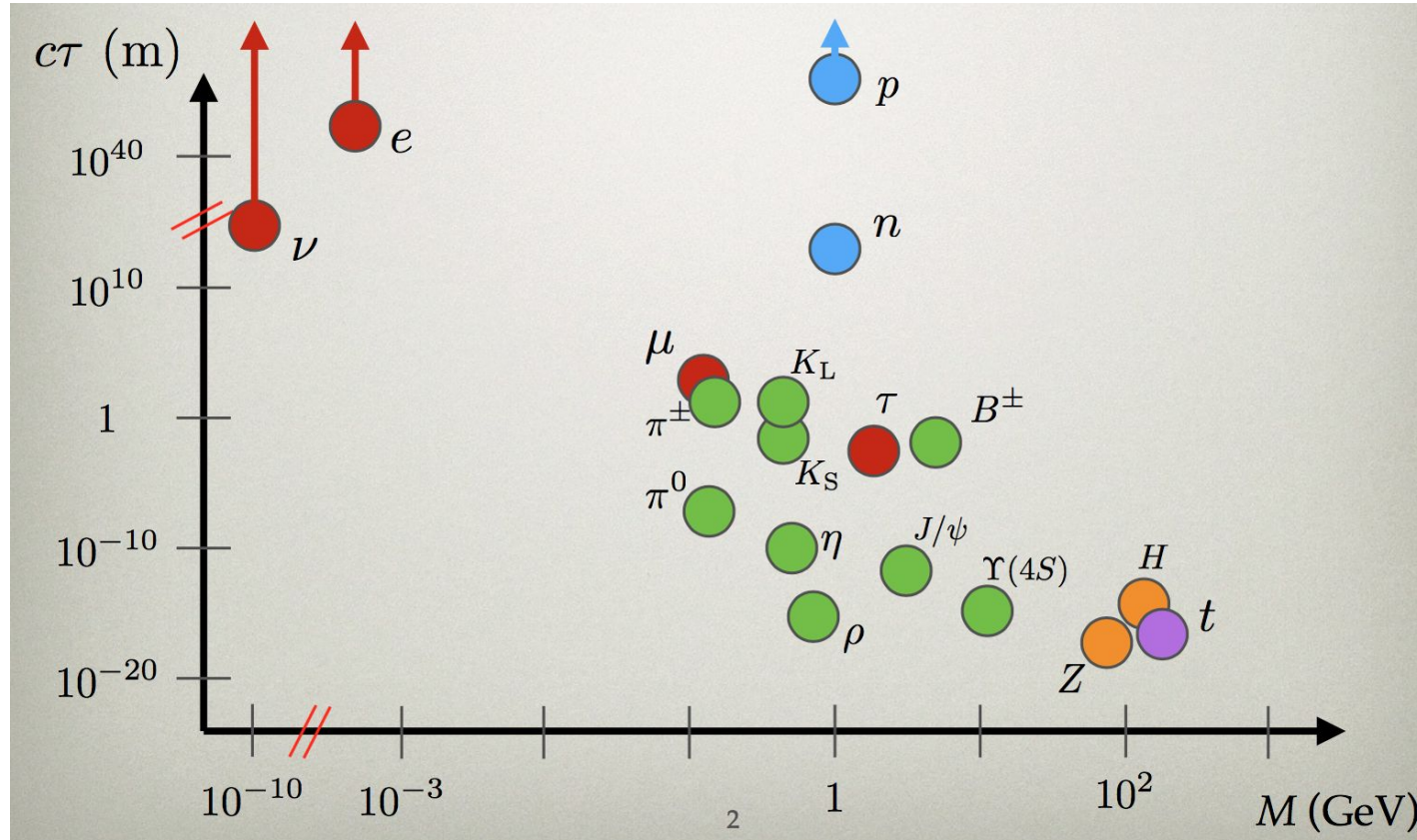
Unknown physics

Neutrino physics

Flavor physics

Hidden Sector

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 ...

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



Source: [wikipedia.org](https://en.wikipedia.org),
[nobelprize.org](https://www.nobelprize.org)



.. 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

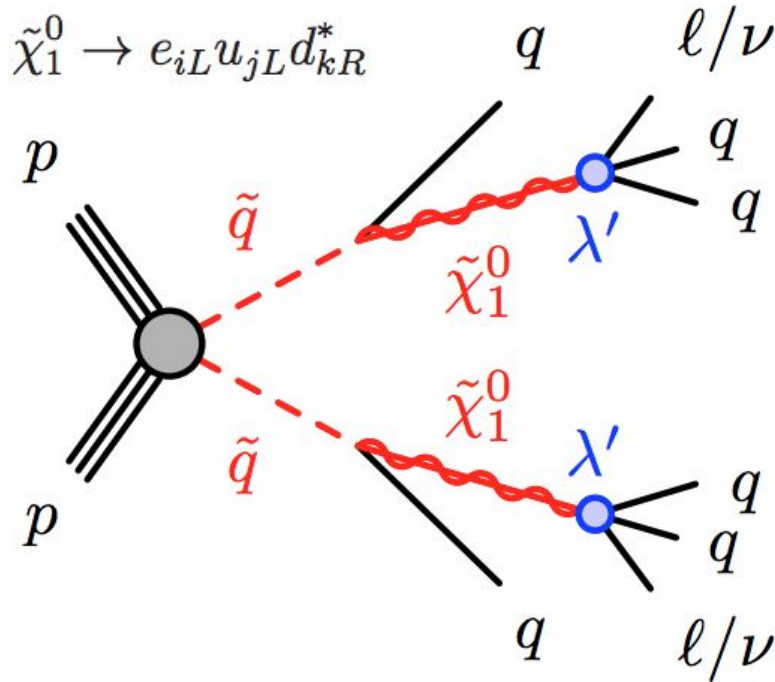
Supersymmetry : R-parity violating SUSY

RPV:

R. Barbier et al, [Phys.Rept. 420 \(2005\)](#)

H. K. Dreiner, G. G. Ross, [Nucl. Phys. B365 \(1991\)](#)

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



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

Small couplings give rise to
macroscopic neutralino lifetime

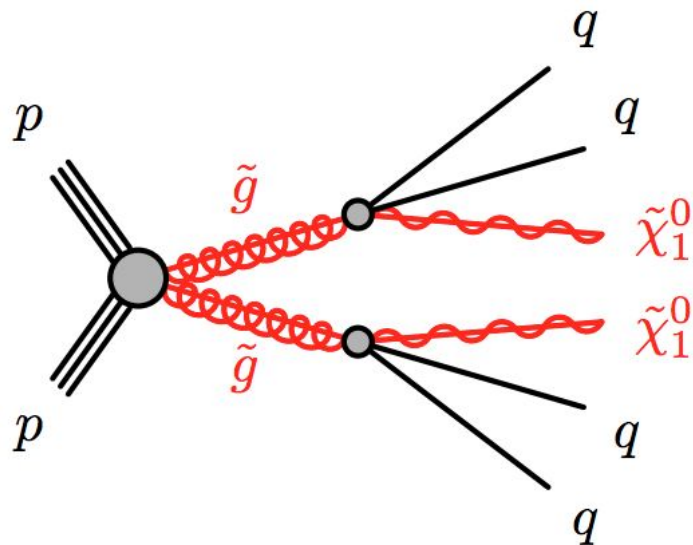
Supersymmetry : split SUSY

Split SUSY:

N. Arkani-Hamed and S. Dimopoulos, , [JHEP 0506 \(2005\) 073](#)

G. Giudice and A. Romanino, [Nucl.Phys. B699 \(2004\)](#)

Heavy SUSY scalars



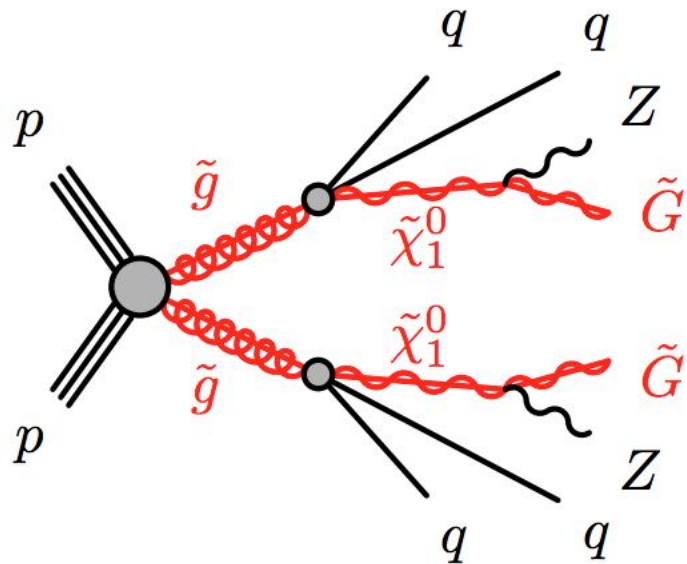
$$c\tau \simeq 2 \times 10^{-1} \left(\frac{2 \text{ TeV}}{M_3} \right)^5 \left(\frac{\tilde{m}}{10^6 \text{ GeV}} \right)^4 \text{ mm}$$

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



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

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 \(1980\)](#)

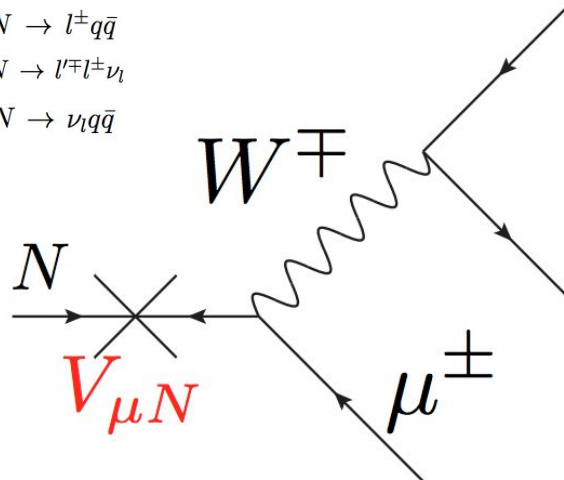
J. Schechter and J. W. F. Valle, [Phys. Rev. D22, 2227 \(1980\)](#)

$$pp \rightarrow W^\pm \rightarrow N l^\pm$$

$$N \rightarrow l^\pm q \bar{q}$$

$$N \rightarrow l'^\mp l^\pm \nu_l$$

$$N \rightarrow \nu_l q \bar{q}$$



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

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

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 \(2014\)](#)

See also [Hiroyuki Ishida](#) and
[Xing-Bo Yuan](#)'s talks !

Sterile Neutrinos : Left-Right Symmetric model

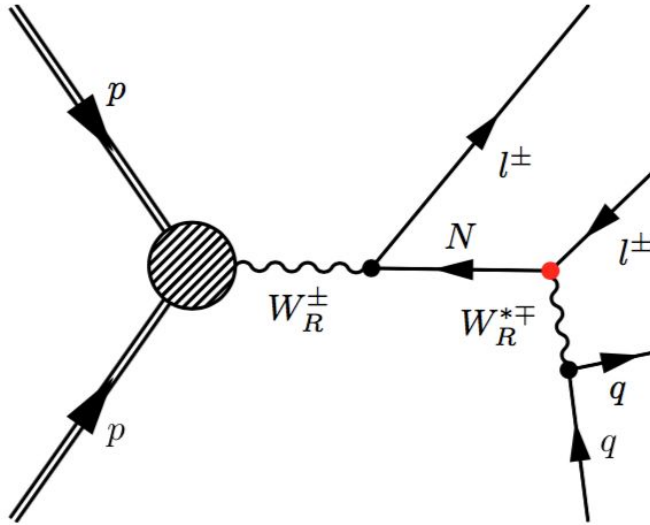
LR model:

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 \(1981\)](#)

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



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

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

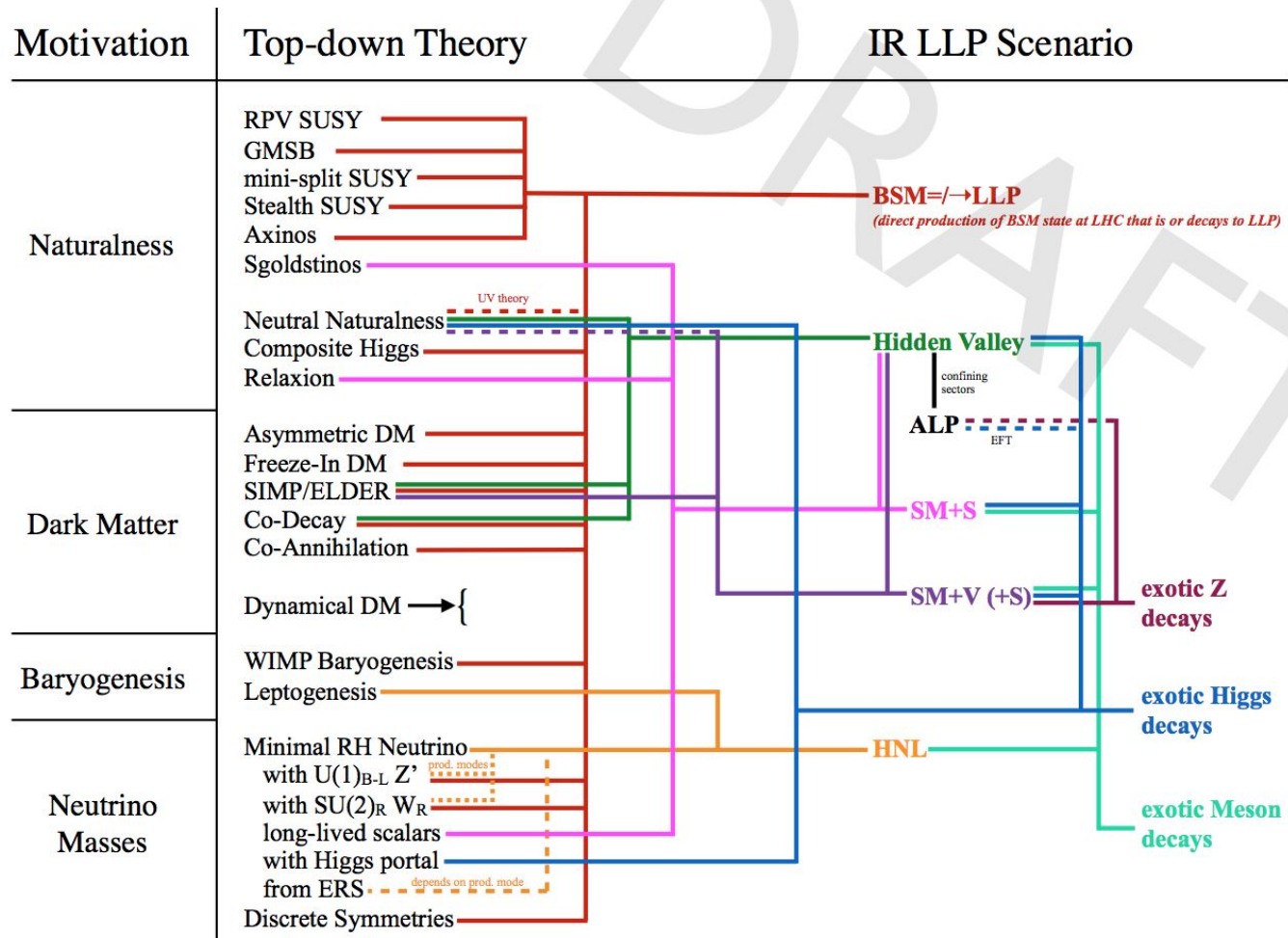
Some displaced LR studies in:

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

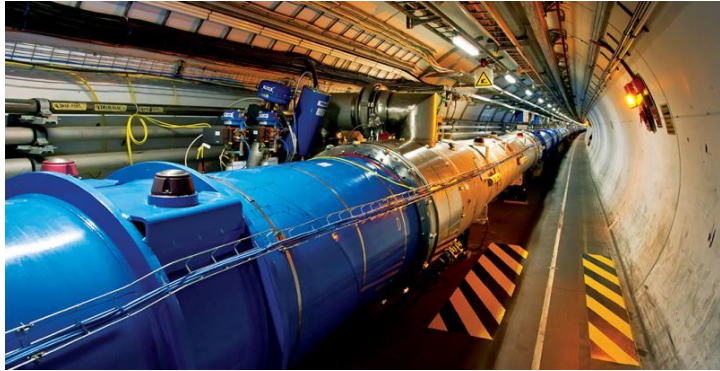


See also M. C. Chu,
 P. Q. Hung, H. M.
 Lee, M. Spinrath, S.
 Sun, Y. Tsai and
 Sming 's talk !

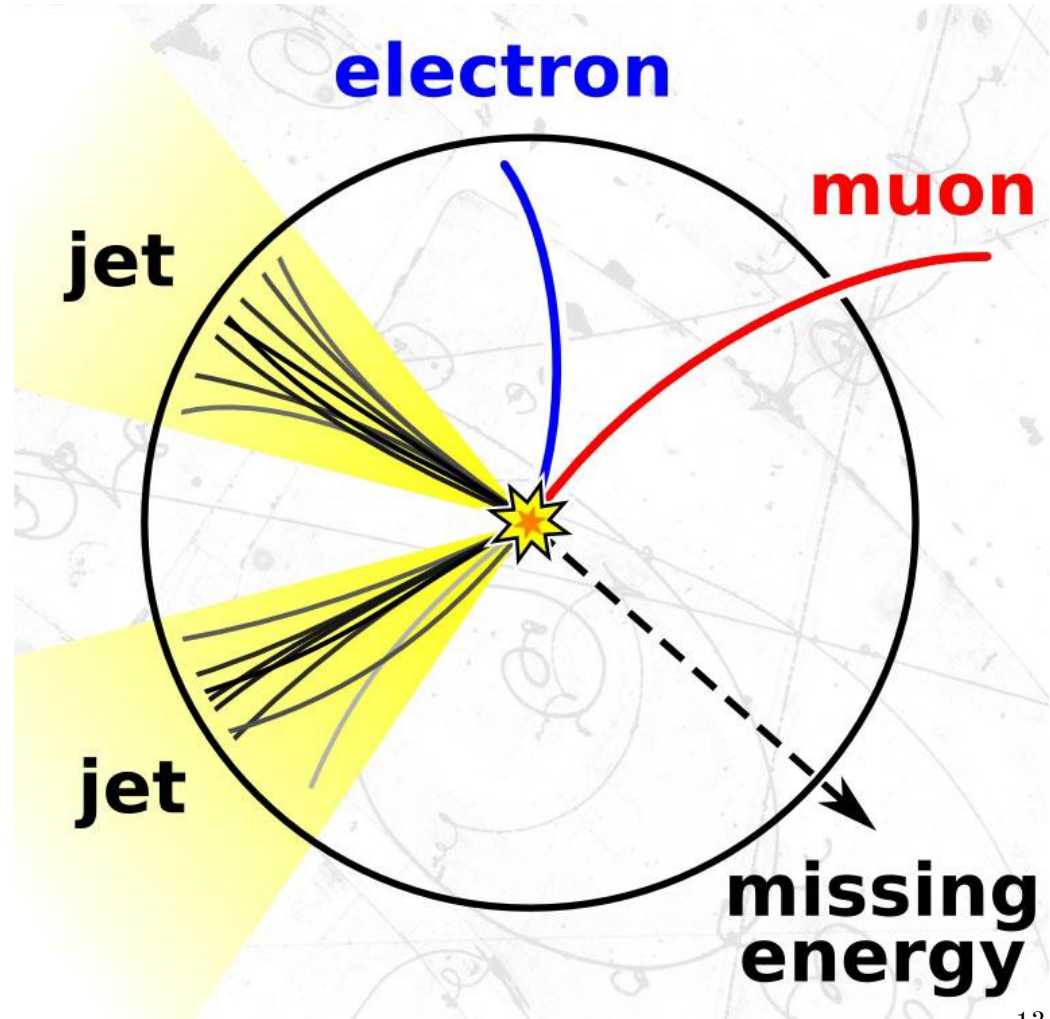


How do we look for all of this new physics at colliders ?

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

ATLAS Exotics Searches* - 95% CL Upper Exclusion Limits

Status: July 2017

ATLAS Preliminary

$$\int \mathcal{L} dt = (3.2 - 37.0) \text{ fb}^{-1}$$

$$\sqrt{s} = 8, 13 \text{ TeV}$$

Model	ℓ, γ	Jets†	E_T^{miss}	$\int \mathcal{L} dt [\text{fb}^{-1}]$	Limit	Reference
Extra dimensions	ADD $G_{KK} + g/q$	$0, e, \mu$	1-4 J	Yes	36.1	$M_{\text{D}} = 7.75 \text{ TeV}$
	ADD non-resonant $\gamma\gamma$	2γ	-	-	36.7	$M_{\text{D}} = 8.6 \text{ TeV}$
	ADD QBH	-	2 J	-	37.0	$M_{\text{BH}} = 8.9 \text{ TeV}$
	ADD BH high $\sum p_T$	$\geq 1, e, \mu$	≥ 2 J	-	3.2	$M_{\text{BH}} = 8.2 \text{ TeV}$
	ADD BH multijet	-	≥ 3 J	-	3.6	$M_{\text{BH}} = 9.55 \text{ TeV}$
	RS1 $G_{KK} \rightarrow \gamma\gamma$	2γ	-	-	36.7	$k/M_{\text{Pl}} = 0.1$
Gauge bosons	Bulk RS $G_{KK} \rightarrow WW \rightarrow q\bar{q}l\nu$	$1, e, \mu$	1 J	Yes	36.1	$k/M_{\text{Pl}} = 1.0$
	2UED / RPP	$1, e, \mu$	$\geq 2, b, \tau, \gamma$	Yes	13.2	Tier (1,1), $R(A^{(1,1)} \rightarrow t\bar{t}) = 1$
	SSM $Z' \rightarrow \ell\ell$	$2, e, \mu$	-	-	36.1	Z' mass
Gauge bosons	SSM $Z' \rightarrow \tau\tau$	2τ	-	-	36.1	Z' mass
	Leptophobic $Z' \rightarrow b\bar{b}$	-	2b	-	3.2	Z' mass
	Leptophobic $Z' \rightarrow t\bar{t}$	$1, e, \mu$	$\geq 1, b, \tau, \gamma$	Yes	3.2	Z' mass
	SSM $W' \rightarrow \ell\nu$	$1, e, \mu$	-	-	36.1	W' mass
	HVT $V' \rightarrow WW \rightarrow q\bar{q}q\bar{q}$ model B	$0, e, \mu$	2 J	-	36.7	V' mass
	HVT $V' \rightarrow WH/ZH$ model B	$1, e, \mu$	2b, 0.4 J	Yes	20.3	V' mass
CI	LRSM $W_2' \rightarrow tb$	$1, e, \mu$	2b, 0.4 J	Yes	20.3	W_2' mass
	LRSM $W_2' \rightarrow tb$	$0, e, \mu$	$\geq 1, b, 1, J$	-	20.3	W_2' mass
CI	CI $q\bar{q}q$	-	2 J	-	37.0	A
	CI $\ell\ell q\bar{q}$	$2, e, \mu$	-	-	36.1	A
DM	CI $u\bar{u}t\bar{t}$	$2(S\bar{S})/2\bar{3} e, \mu$	$\geq 1, b, \tau, \gamma$	Yes	20.3	A
	Vector mediator (Dirac DM)	$0, e, \mu$	1-4 J	Yes	36.1	m_{DM}
LQ	Vector mediator (Dirac DM)	$0, e, \mu$	$1, \gamma$	-	36.1	m_{DM}
	VV $_{\text{XX}}$ EFT (Dirac DM)	$0, e, \mu$	$1, 4, 1, 2$	Yes	3.2	M_{XX}
Heavy quarks	Scalar LQ 1^{st} gen	$2, e$	≥ 2 J	-	3.2	LQ mass
	Scalar LQ 2^{nd} gen	$2, \mu$	≥ 2 J	-	3.2	LQ mass
	Scalar LQ 3^{rd} gen	$1, e, \mu$	$\geq 1, b, \tau, \gamma$	Yes	20.3	LQ mass
Excited fermions	VLO $QT \rightarrow Ht + X$	$0 \text{ or } 1, e, \mu$	$\geq 2, b, \tau, \gamma$	Yes	13.2	T mass
	VLO $QT \rightarrow Zt + X$	$1, e, \mu$	$\geq 1, b, \tau, \gamma$	Yes	36.1	T mass
	VLO $QT \rightarrow Wb + X$	$1, e, \mu$	$\geq 1, b, \tau, \gamma$	Yes	36.1	T mass
	VLO $QB \rightarrow Hb + X$	$1, e, \mu$	$\geq 2, b, \tau, \gamma$	Yes	20.3	B mass
	VLO $QB \rightarrow Zb + X$	$2, 3, e, \mu$	$\geq 2, b, \tau, \gamma$	Yes	20.3	B mass
	VLO $QB \rightarrow Wt + X$	$1, e, \mu$	$\geq 1, b, \tau, \gamma$	Yes	36.1	B mass
Excited fermions	VLO $Q\bar{Q} \rightarrow WqWq$	$1, e, \mu$	$\geq 1, b, \tau, \gamma$	Yes	20.3	Q mass
	Excited quark $q^* \rightarrow qg$	-	2 J	-	37.0	q^* mass
	Excited quark $q^* \rightarrow q\gamma$	1γ	1 J	-	36.7	q^* mass
	Excited quark $q^* \rightarrow qg$	-	1b, 1 J	-	13.3	q^* mass
	Excited quark $q^* \rightarrow Wt$	$1 \text{ or } 2, e, \mu$	1b, 2b, 0 J	Yes	20.3	q^* mass
	Excited lepton ℓ^*	$3, e, \mu$	-	-	20.3	ℓ^* mass
Excited fermions	Excited lepton ν^*	$3, e, \mu, \tau$	-	-	20.3	ν^* mass
	LRSM Majorana ν	$2, e, \mu$	2 J	-	20.3	ν^* mass
	Higgs triplet $H^{\pm\pm} \rightarrow \ell\ell$	$2, 3, 4, e, \mu$ (SS)	-	-	36.1	$H^{\pm\pm}$ mass
	Higgs triplet $H^{\pm\pm} \rightarrow \tau\tau$	$3, e, \mu, \tau$	-	-	20.3	$H^{\pm\pm}$ mass
	Monopole (non-res prod)	$1, e, \mu$	1b	Yes	20.3	μ_{mon}
	Multi-charged particles	-	-	-	20.3	μ_{multi}
Other	Magnetic monopoles	-	-	-	7.0	μ_{magnetic}
	Phenomena	-	-	-	7.0	$\mu_{\text{phenomena}}$

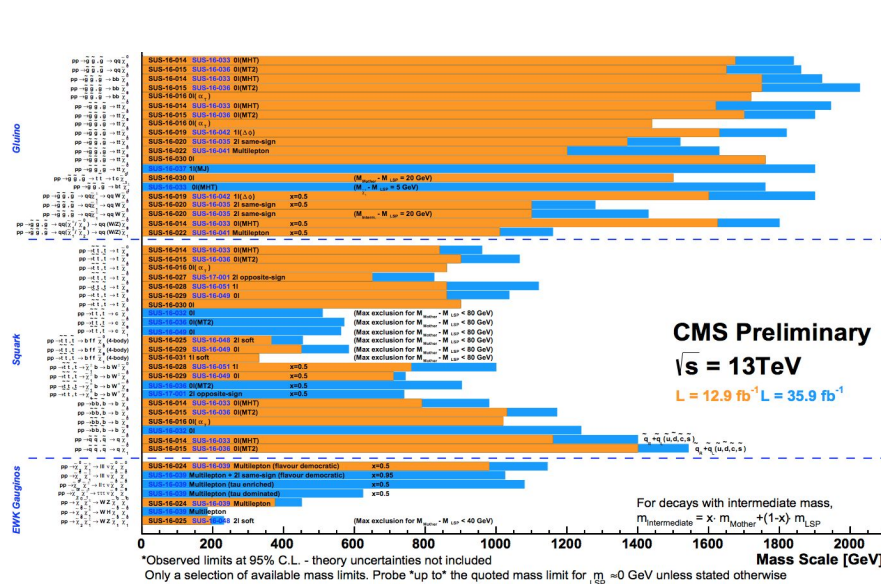
$\sqrt{s} = 8 \text{ TeV}$

$\sqrt{s} = 13 \text{ TeV}$

*Only a selection of the available mass limits on new states or phenomena is shown.

†Small-radius (large-radius) jets are denoted by the letter J (J).

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



CMS Preliminary

$\sqrt{s} = 13 \text{ TeV}$

$L = 12.9 \text{ fb}^{-1} \pm 35.9 \text{ fb}^{-1}$

For decays with intermediate mass,

$$m_{\text{intermediate}} = x \cdot m_{\text{mother}} \cdot (1-x) \cdot m_{\text{LSP}}$$

*Observed limits at 95% C.L. - theory uncertainties not included
Only a selection of available mass limits. Probe *up to* the quoted mass limit for $m_{\text{LSP}} = 0 \text{ GeV}$ unless stated otherwise

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

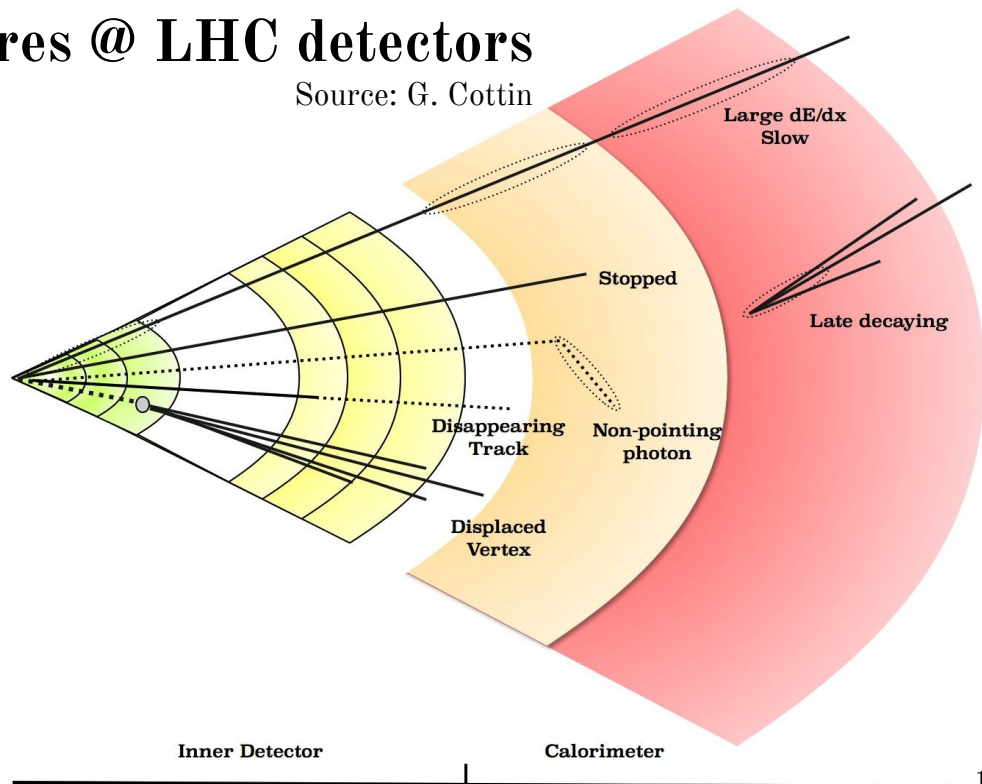
Long-Lived Particle Signatures @ LHC detectors

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 !

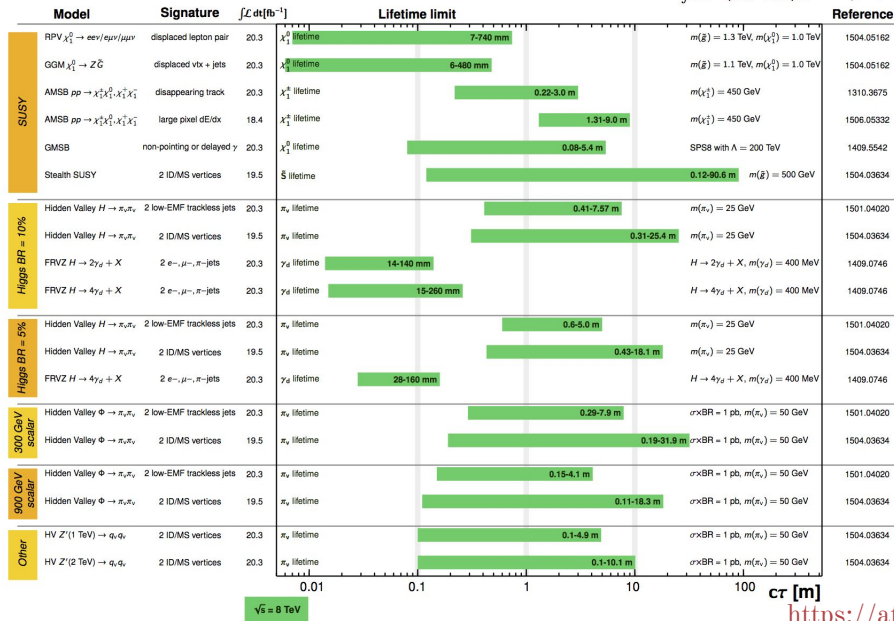


BUT sadly, ALSO no signs of new physics

ATLAS Long-lived Particle Searches* - 95% CL Exclusion

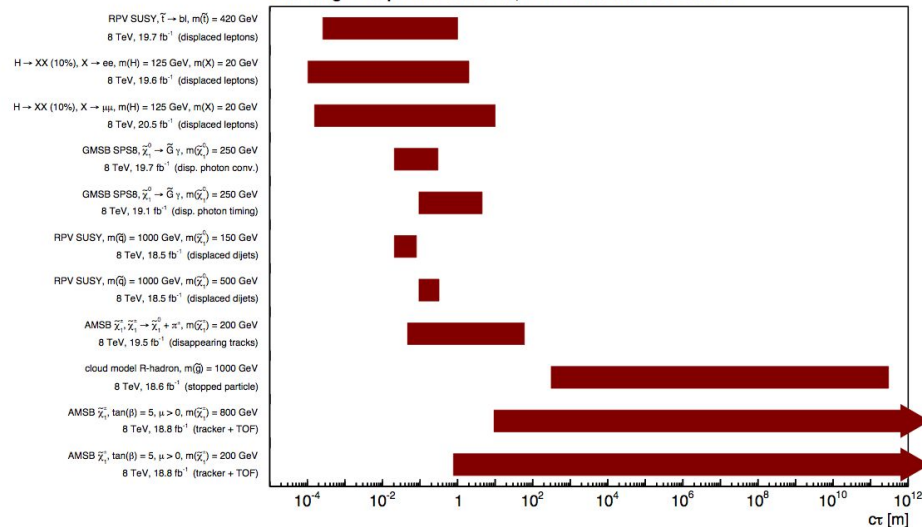
Status: July 2015

ATLAS Preliminary
 $\int \mathcal{L} dt = (18.4 - 20.3) \text{ fb}^{-1}$
 $\sqrt{s} = 8 \text{ TeV}$



*Only a selection of the available lifetime limits on new states is shown.

CMS long-lived particle searches, lifetime exclusions at 95% CL



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

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

Displaced Vertex signatures @ LHC detectors
Source: G. Cottin

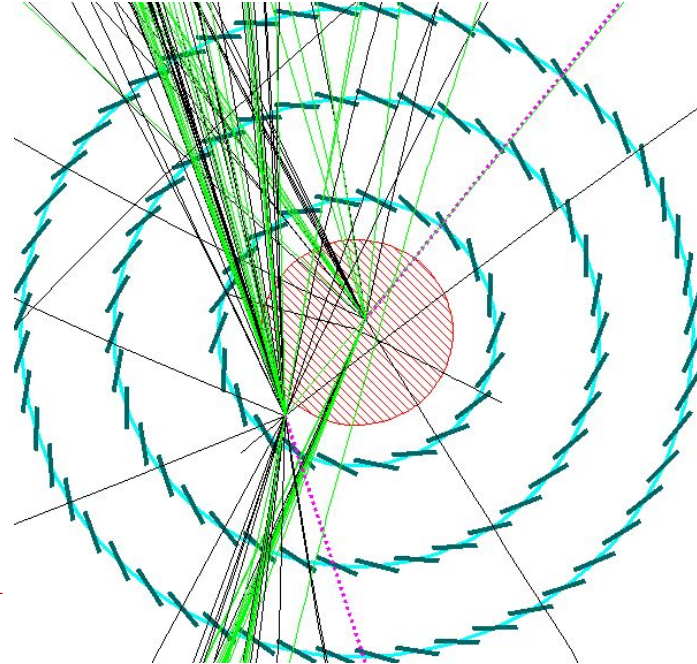




Image credit: Richard Jacobsson and Daniel Dominguez. Source : <http://cerncourier.com/cws/article/cern/63982>