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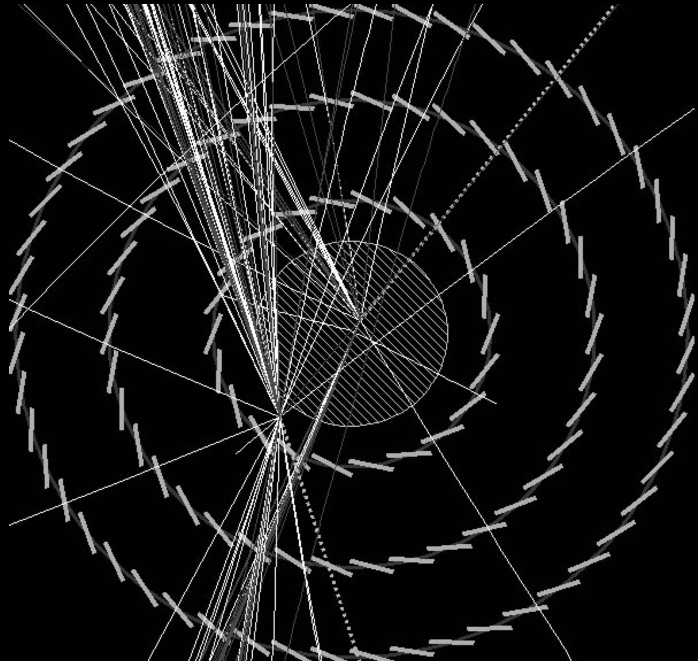
Simplified Models for Long-Lived Particles and Reinterpretation of LHC searches



Giovanna Cottin

Cavendish/DAMTP Seminar
November 2019

Some fundamental questions

What is matter made of?

What is the "dark matter" we observe?

Why is there more matter than antimatter?

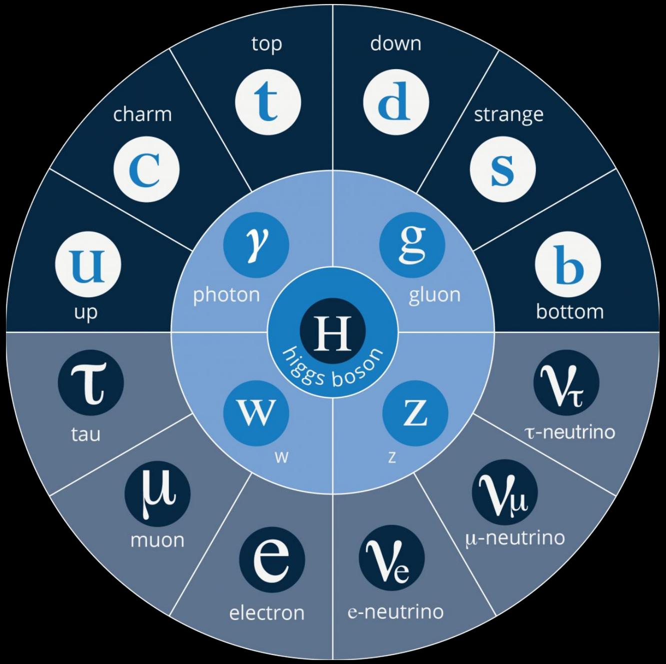
Are there more new forces we haven't detected yet?

Why is gravity so different than the other three known fundamental forces?

Can we describe all forces between particles in a unified framework?

What is matter made of?

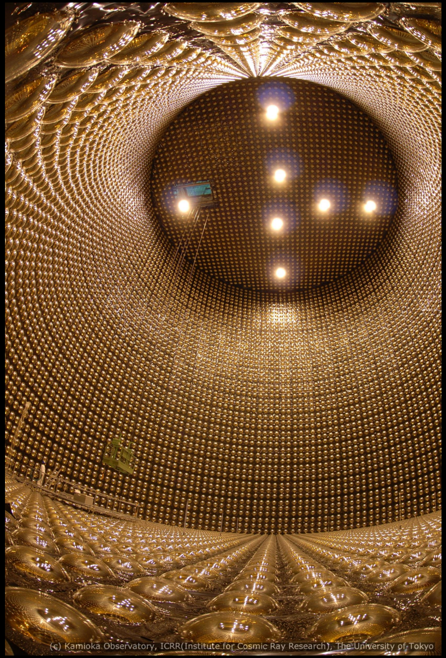
The Standard Model of matter and its interactions

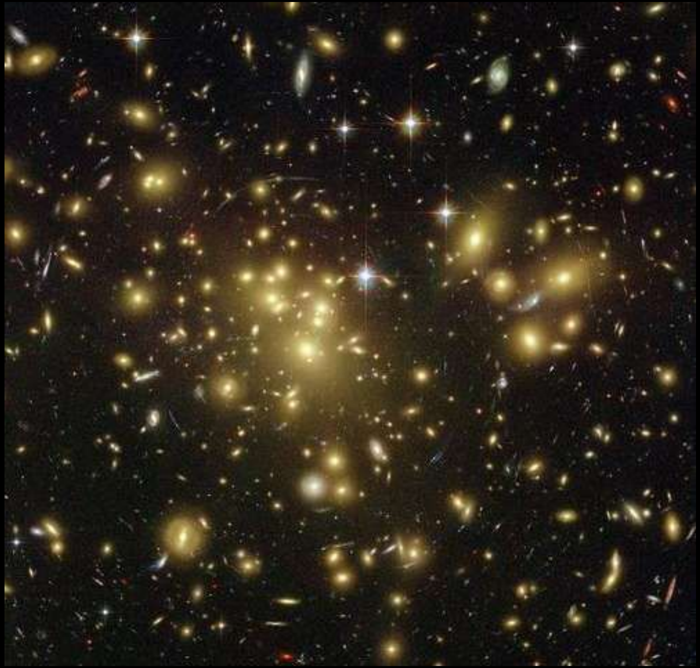


Source : https://atlas.cern/discover/physics

Is there anything else ?

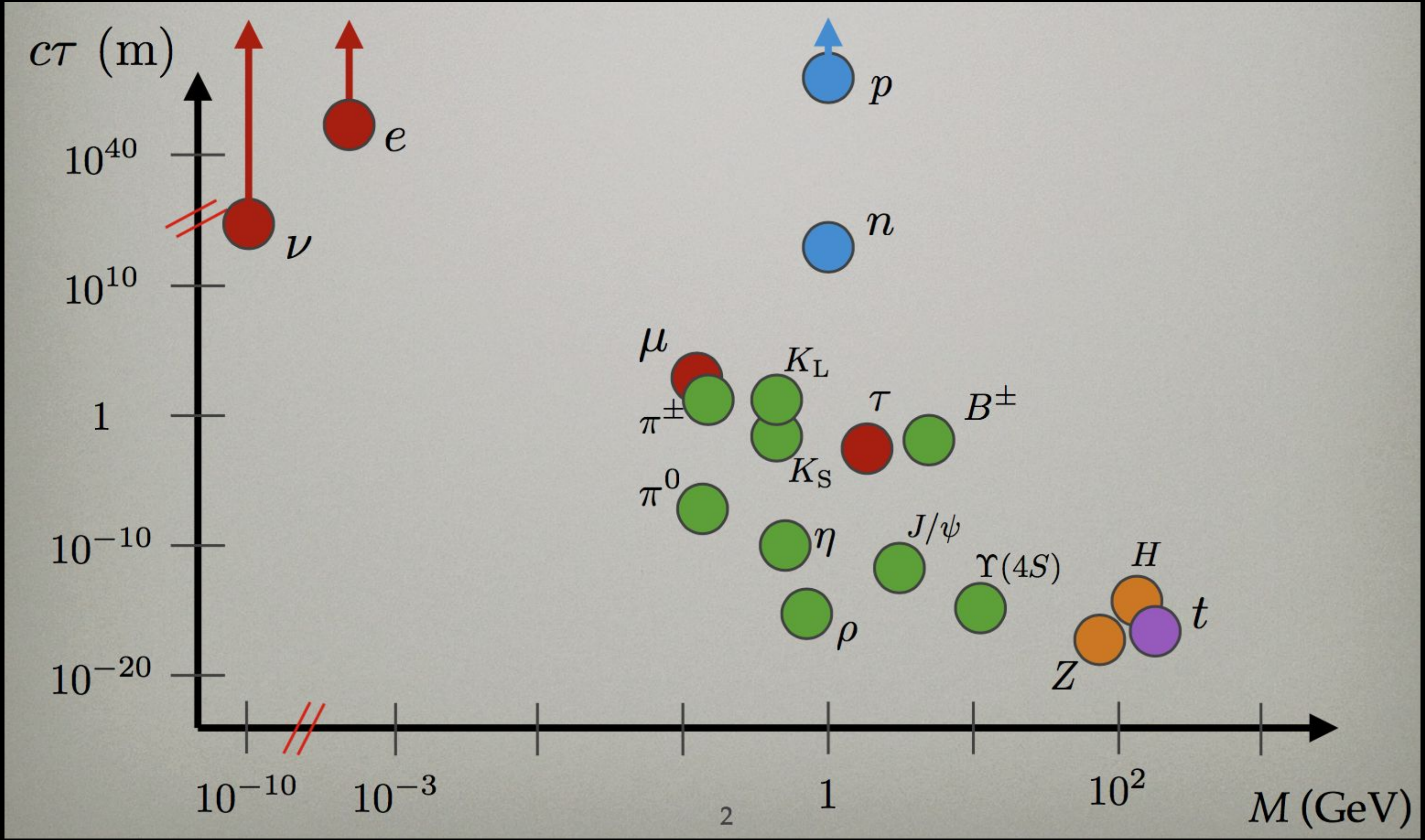
We have reasons to believe so !





Source: http://www-sk.icrr.u-tokyo.ac.jp/sk/gallery/index-e.html
https://phys.org/news/2015-03-dark.html

This is what we know today

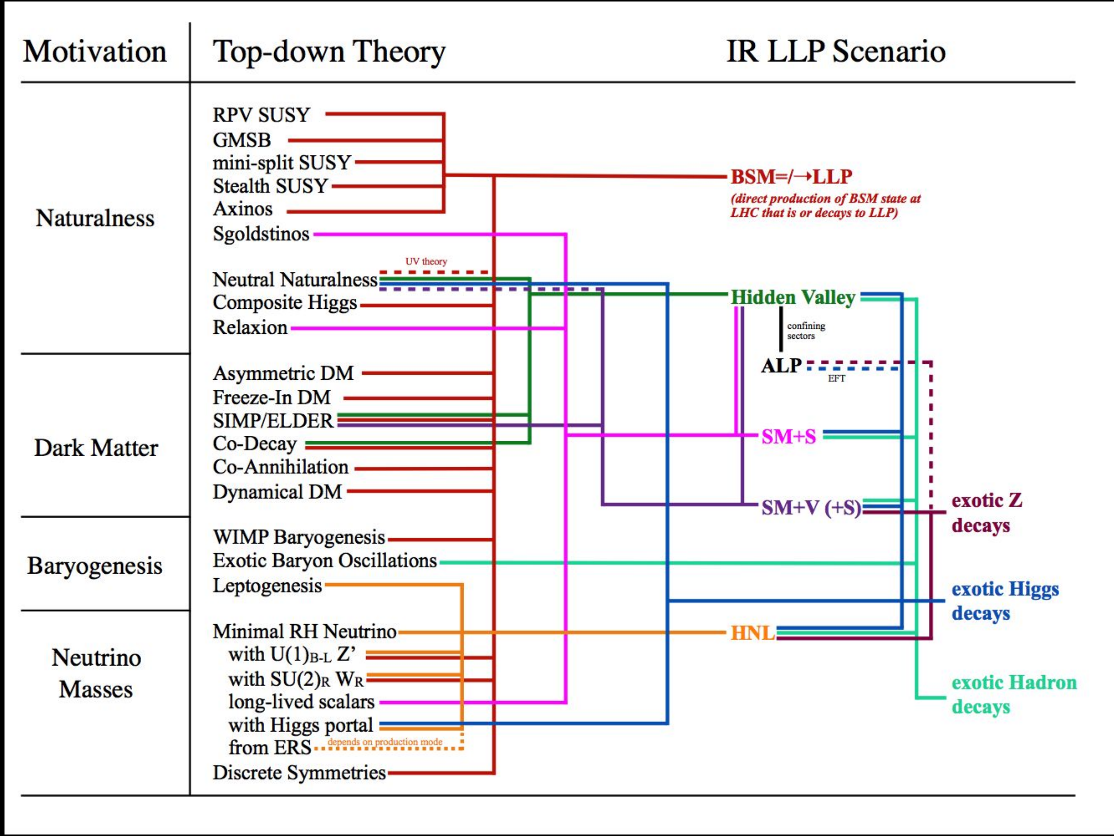


The presence of LLPs comes from conserved symmetries, small couplings or heavy mediators

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

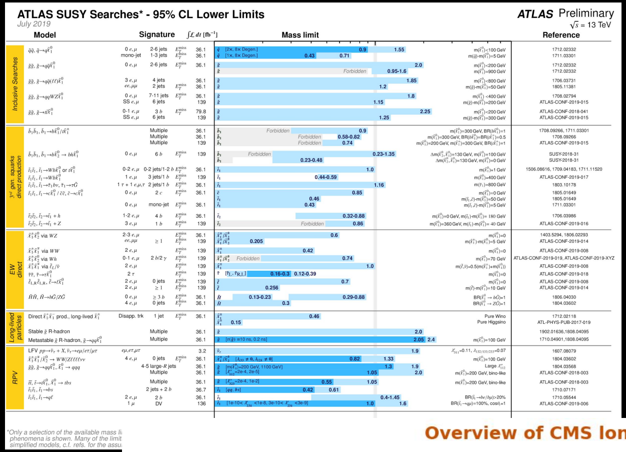
Why shouldn't an exotic sector of particles share the same structure?

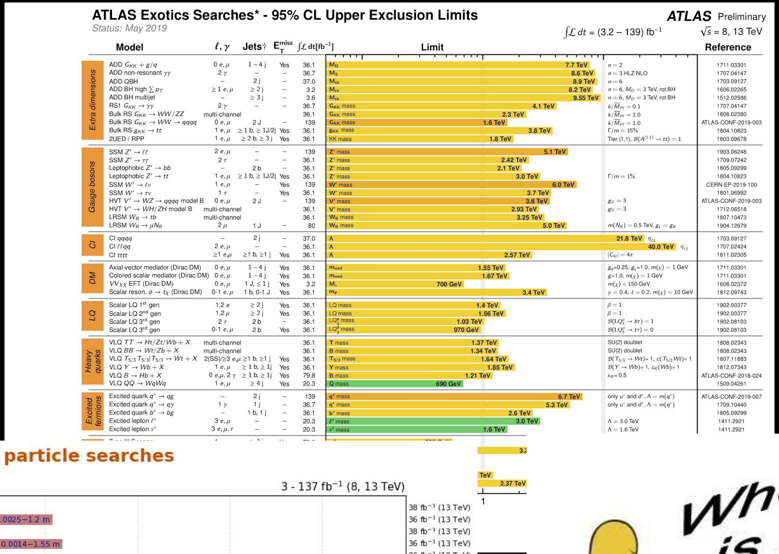
No reason! We expect plenty of new, long-lived particles beyond the Standard Model

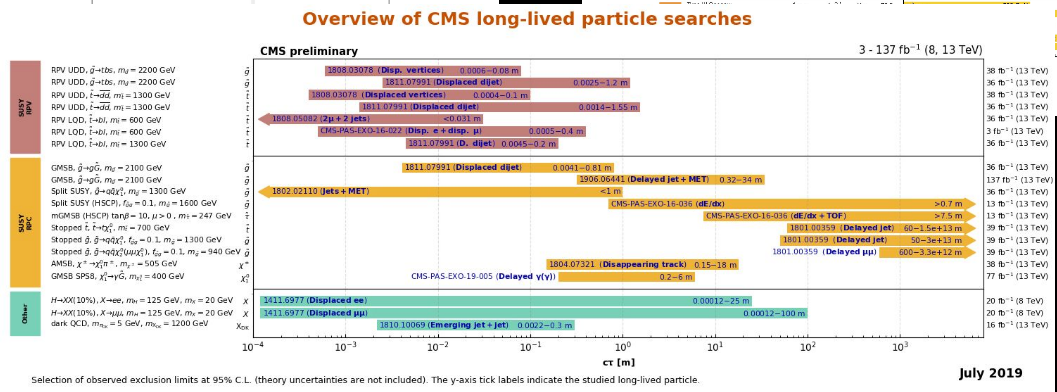


Source: MATHUSLA physics [arXiv:1806.07396]

But … where is it? We haven't seen any of these models @ the LHC ! LLPs are ubiquitous in all of them.

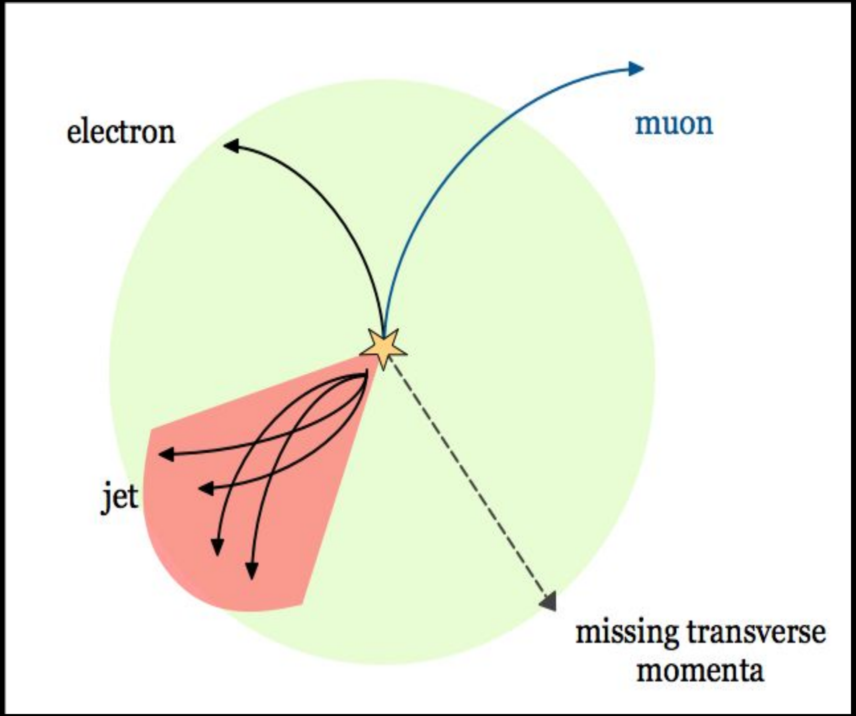




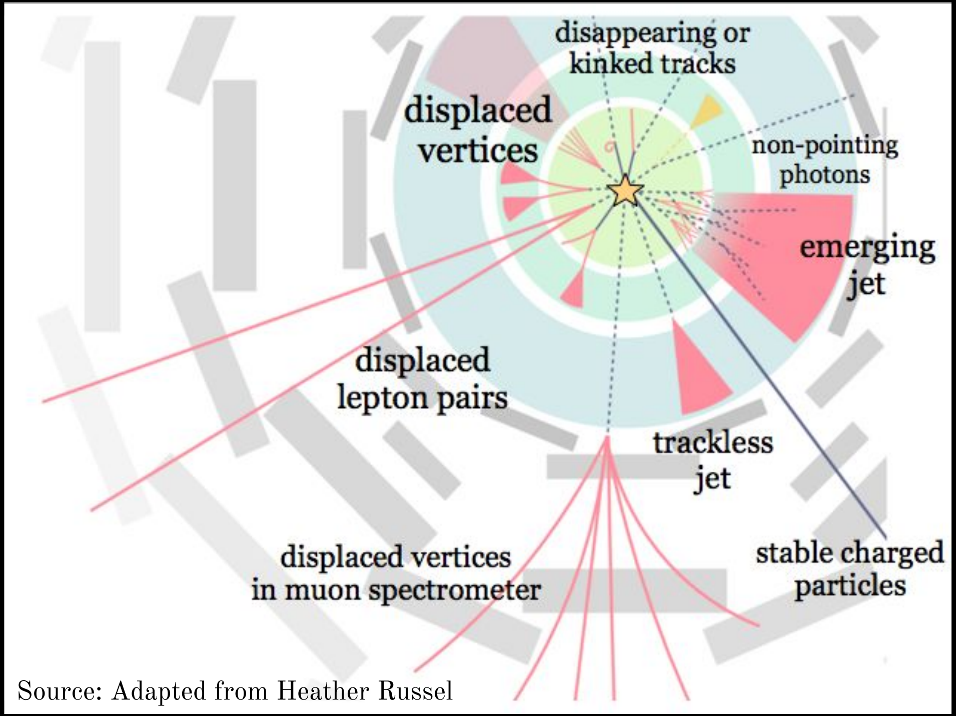


Maybe the new physics is hidden in more exotic decay patterns. We should carefully extend our physics program to look everywhere !

Standard Prompt Signatures



Exotic LLP Signatures



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

Current status of LLP searches @ LHC

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

March 6, 2019

Particles beyond the Standard Model (SM) can generically have lifetimes that are long compared to SM particles at the weak scale. When produced at experiments such as the Large Hadron Collider (LHC) at CERN, these long-lived particles (LLPs) can decay far from the interaction vertex of the primary proton-proton collision. Such LLP signatures are distinct from those of promptly decaying particles that are targeted by the majority of searches for new physics at the LHC, often requiring customized techniques to identify, for example, significantly displaced decay vertices, tracks with atypical properties, and short track segments. Given their non-standard nature, a comprehensive overview of LLP signatures at the LHC is beneficial to ensure that possible avenues of the discovery of new physics are not overlooked. Here we report on the joint work of a community of theorists and experimentalists with the ATLAS, CMS, and LHCb experiments — as well as those working on dedicated experiments such as MoEDAL, milliQan, MATHUSLA, CODEX-b, and FASER — to survey the current state of LLP searches at the LHC, and to chart a path for the development of LLP searches into the future, both in the upcoming Run 3 and at the High-Luminosity LHC. The work is organized around the current and future potential capabilities of LHC experiments to generally discover new LLPs, and takes a signature-based approach to surveying classes of models that give rise to LLPs rather than emphasizing any particular theory motivation. We develop a set of simplified models; assess the coverage of current searches; document known, often unexpected backgrounds; explore the capabilities of proposed detector upgrades; provide recommendations for the presentation of search results; and look towards the newest frontiers, namely high-multiplicity "dark showers", highlighting opportunities for expanding the LHC reach for these signals.

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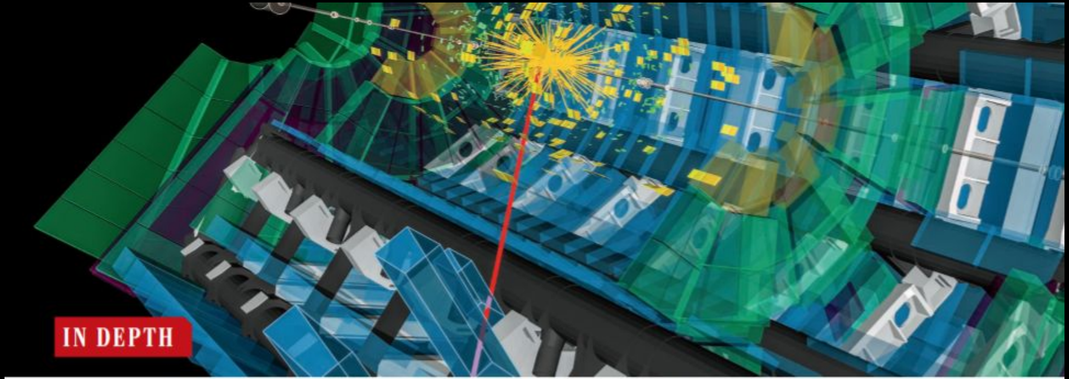
Source: LLP community whitepaper arXiv:1903.04497, Accepted in J. Phys. G !

LLPs on *Science* in May !



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

https://www.sciencemag.org/news/2019/05/atom-smasher-could-be-making-new-particles-are-hiding-plain-sight

Outline

LLPs at the LHC : Searches for non-standard signatures

- We have developed Simplified Models to systemize these searches
- Searches are difficult. Reinterpretation of them to other physics models is not always straightforward. Information from the experiments in appropriate format is essential
- We have identified reinterpretation challenges and ways to address them. I will give some examples
- LLP Summary and future roadmap

Briefly going back to BSM models. We can classify in 5 overarching categories the models yielding LLPs

Motivation

Dark Matter
Baryogenesis
Neutrino Masses
Naturalness

Theory

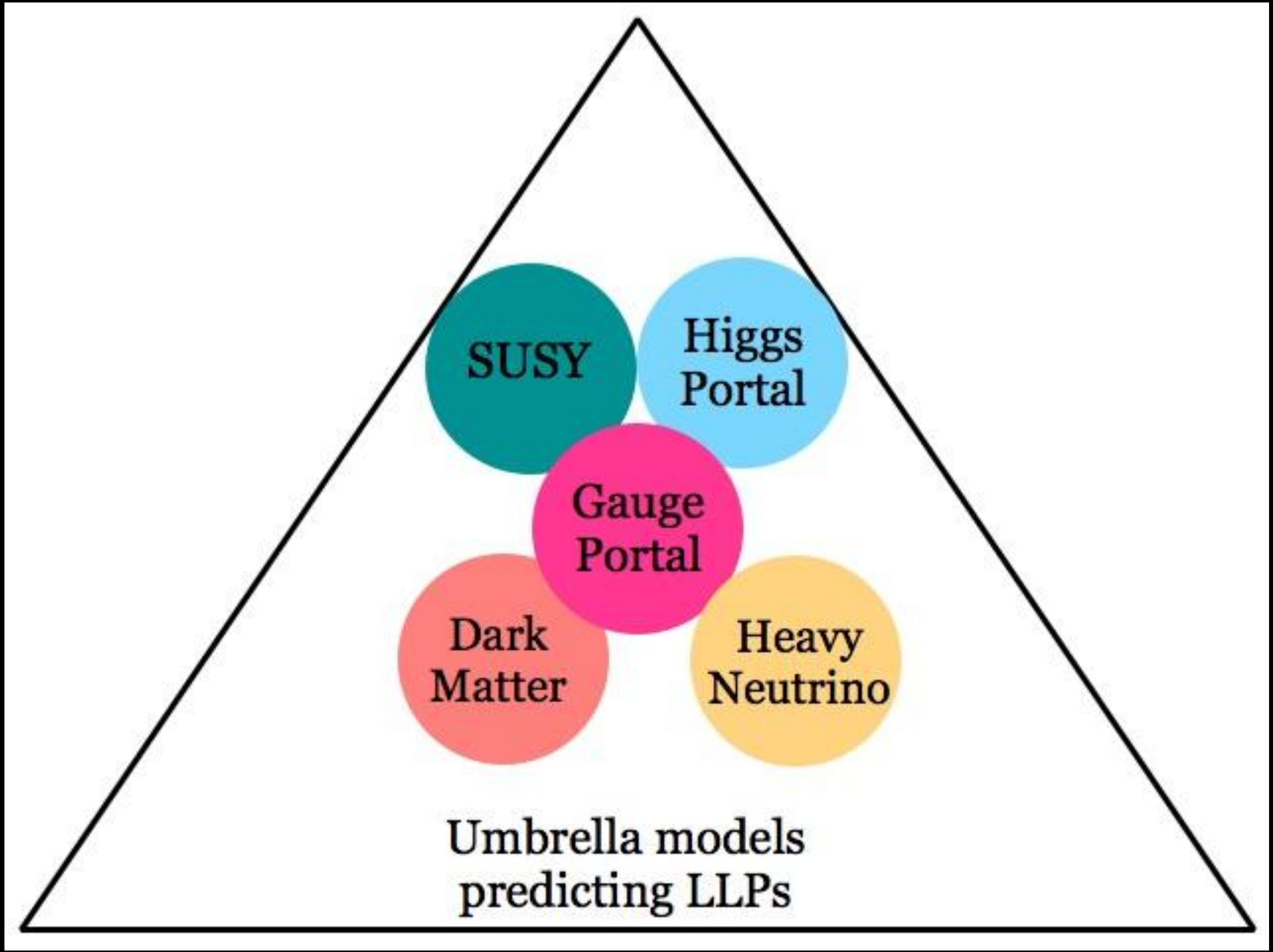
SUSY Multiple LLPs with SM gauge charges RPV, split SUSY

Higgs Portal LLPs predominantly coupled to the Higgs Hidden Valley

Gauge Portal New vector mediators can produce LLPs Z', dark photon

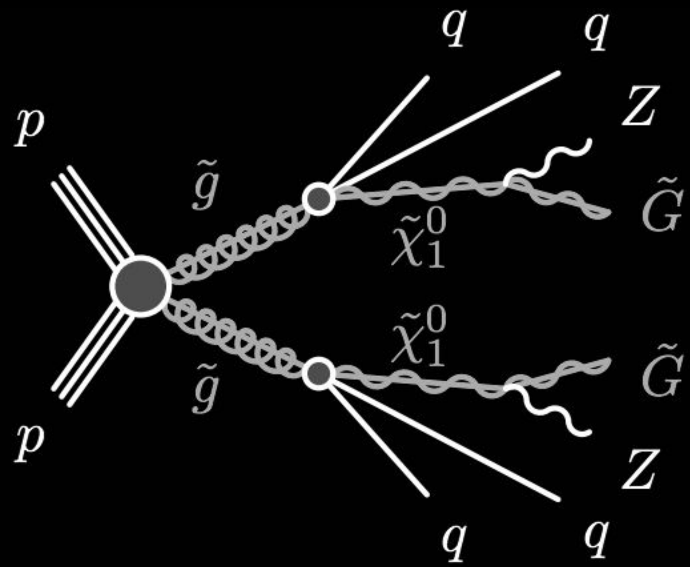
Dark Matter Non SUSY, hidden sector DM produced as final state at colliders EWK Multiplets, FIMP, SIMPs

RH Neutrinos RHnu masses in the GeV to TeV range can be LLP nuMSM, Left-Right Symmetry


SUSY
Higgs Portal
Gauge Portal
Dark Matter
Heavy Neutrino
Umbrella models predicting LLPs

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

SUSY



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

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)

Heavy Neutrino

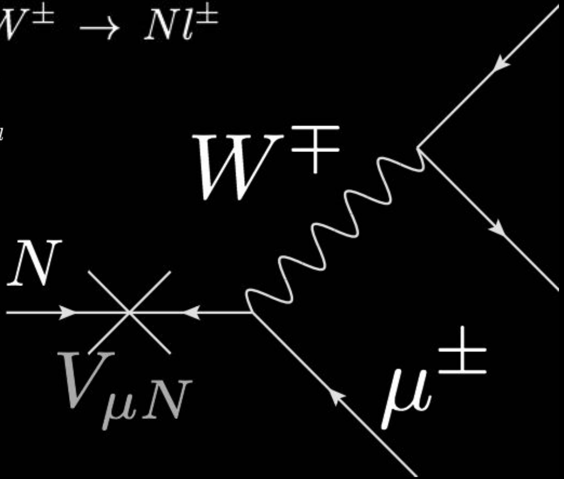
See-saw:
P. Minkowski, Phys. Lett. 67B (1977)
R. N. Mohapatra and G. Senjanovic, Phys. Rev. Lett. 44 (1980)
J. Schechter and J. W. F. Valle, Phys. Rev. D22, 2227 (1980)

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

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

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

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



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

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

displaced N studies in:
G. Cottin, J.C. Helo, M. Hirsch, D. Silva, Phys. Rev. D.99 (2019)
G. Cottin, J.C. Helo and M. Hirsch, Phys. Rev. D97 (2018)
G. Cottin, J.C. Helo and M. Hirsch, Phys. Rev. D98 (2018)
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)

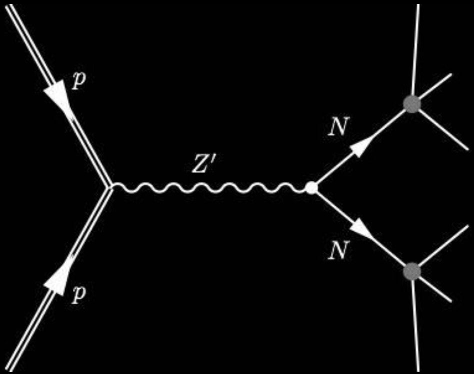
Can construct Simplified Models in umbrella theories

SM are an effective-Lagrangian description with :

* A limited number of new particles considered
* A specific production and decay channels (i.e 100% BR)
* A few free parameters (mainly masses and lifetime)
* A compact and efficient way to benchmark models, as oppose to the design of separate (potentially redundant) searches for each UV model

Gauge Portal

SM Example

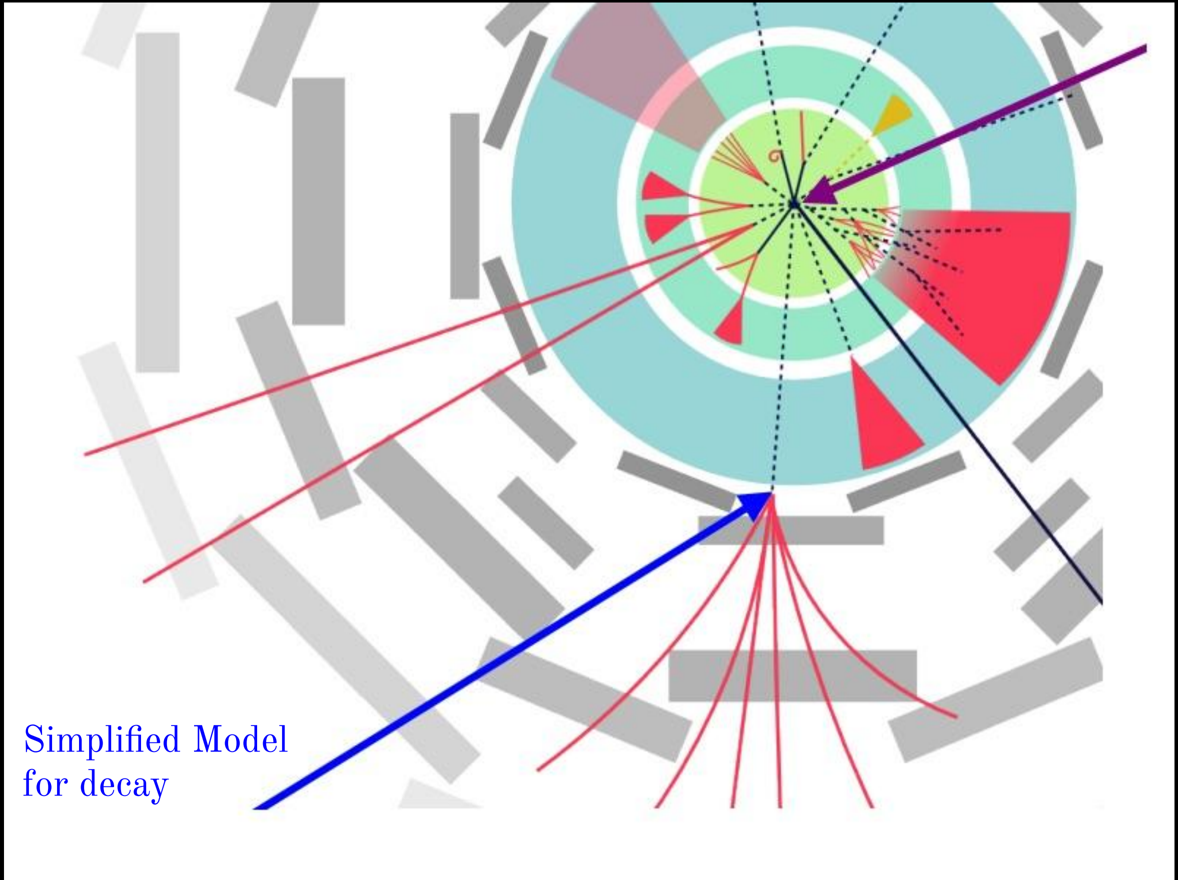


$$\mathcal{L} = \mathcal{L}_{\rm SM} - \frac{1}{4}V_{\mu\nu}^2 - \frac{1}{2}M_V^2 V_\mu^2 + iN^\dagger\bar{\sigma}^\mu\partial_\mu N$$
$$-\frac{M_N}{2}(N^2 + {\rm h.c.}) + g' V_\mu\left(\sum_{\rm SM} Q_{B-L}\psi^\dagger\bar{\sigma}^\mu\psi + N^\dagger\bar{\sigma}^\mu N\right)$$
$$+\theta_{\mu N}\frac{g_W}{\sqrt{2}}\left(\mu_L^\dagger\bar{\sigma}^\mu W_\mu^- N + {\rm h.c.}\right) + \ldots,$$

B. Battel, M. Pospelov and B. Shuve, JHEP 1608 (2016)

Simplified Models Building Blocks: LLP production and LLP decay

Main goal: ensure LHC LLP searches are optimally useful in the future, cover all relevant signatures, and final states

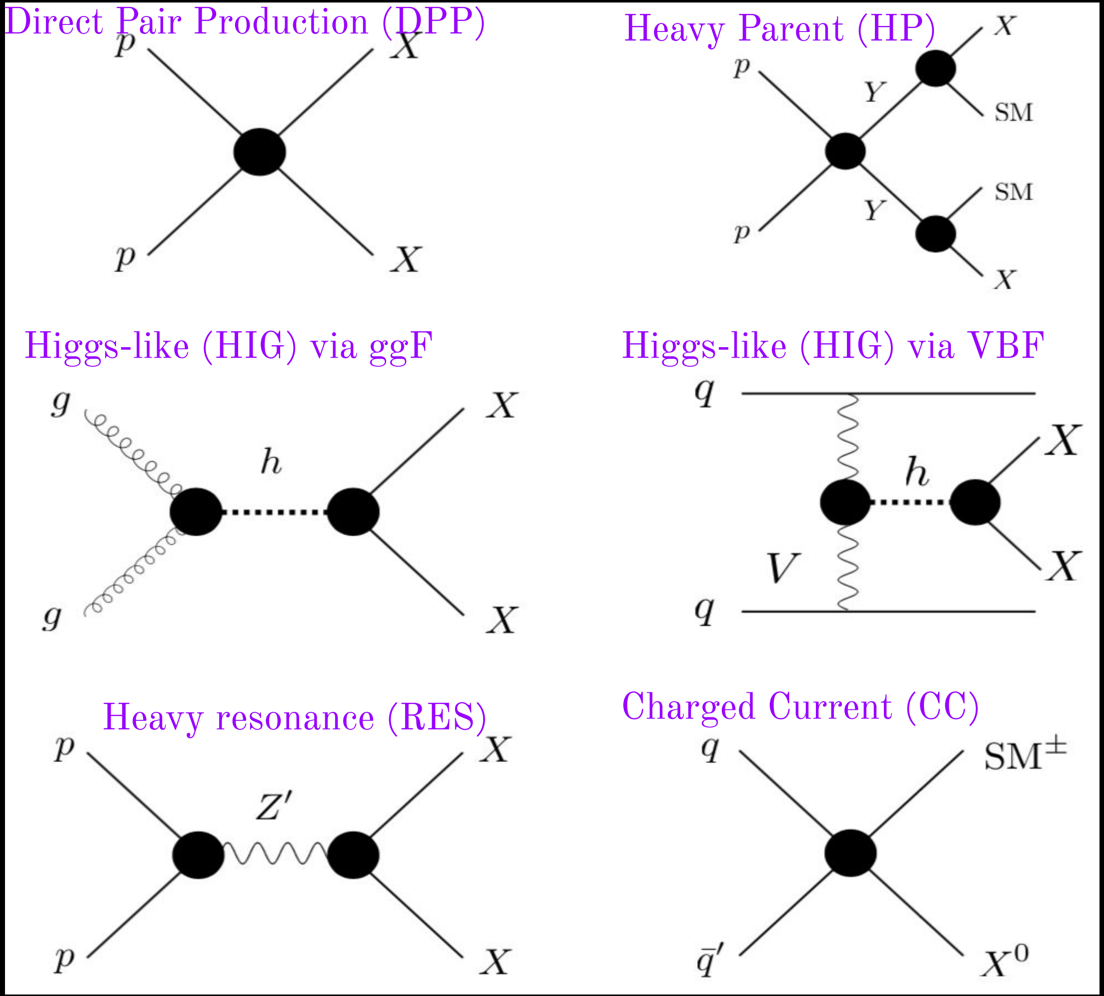


Simplified Model for production

Since particles are long-lived, production & decay modes can factorize ! (except if it hadronizes)

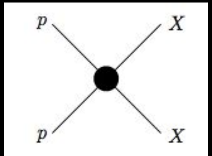
Thanks to B.Shuve @ LHC-LLP workshop, CERN

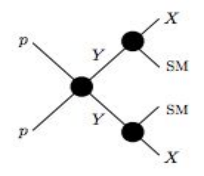
LLP Simplified Model production proposal

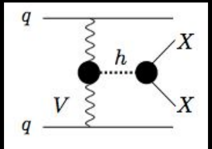


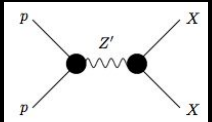
Source: LLP community white paper arXiv:1903.04497

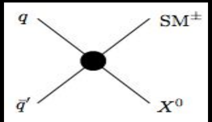
LLP Simplified Model production











Mode	Brief Description	Example Model
Direct Pair Production (DPP)	LLP is pair produced non-resonantly from SM initial states. SM gauge production or heavy offshell field (EFT)	SUSY sneutrinos or electroweak-inos
Heavy Parent (HP)	LLP is produced in the decays of a heavy parent particle. Kinematics depends on mass splitting between parent and LLP	SUSY gluino or squark decaying to neutralino LLP
Higgs (HIG)	LLP can be produced through its couplings to the SM-higgs boson. Characterized by VBF/VH modes & associated objects. Higgs can be off-shell	Twin Higgs models
Heavy Resonance (RES)	Similar to heavy parent, but with only one parent	Hidden portal coupled via Z’
Charged Current (CC)	LLP can be produced in the leptonic decays of a W or W'. Associated charged, prompt SM objects	Right-handed neutrino in minimal or LR-symmetric model

LLP Simplified Model decay

In principle, many possible decay modes !

When do we NOT need to consider so many exclusive decay modes?

- When particle ID in searches loose or not possible (e.g., decays in HCAL)
- When searches highly inclusive (i.e agnostic about other objects coming from decay vertex)

Most LLP searches require at most two identifying objects at the vertex & are otherwise inclusive

- Two leptons (whether reconstructing a vertex or not) CMS-PAS-EXO-16-022
- One lepton + hadrons ATLAS DV 1504.05162

When DO we need to consider so many exclusive decay modes?

- 2-body vs. 3-body kinematics can be different
- We want reinterpreting results to be better than a factor of ~few

Our goal : Try to control multiplicity of possible decays while including enough to cover signature space needed for discovery

With thanks to B.Shuve @ LHC-LLP workshop, CERN

LLP Simplified Model decay

These are highly inclusive ! A given experimental search can be sensitive to many decay modes, due to low bkgs and "looser" particle id in LLP searches arXiv:1903.04497

Mode	Brief Description	Example Model
Diphoton	$X \to \gamma\gamma$ $X \to \gamma\gamma + \not{E}_{\mathrm{T}}$	SUSY: singlino decay to two photons + MET
Single photon	$X \to \gamma + \not{E}_{\mathrm{T}}$	SUSY: Bino decay in gauge mediation
Fully hadronic	$X \to jj$ $X \to j + \not{E}_{\mathrm{T}}$ $X \to jj + \not{E}_{\mathrm{T}}$	Twin Higgs: glueball decay via Higgs mixing
Semileptonic	$X \to \ell_\alpha^\pm + j$ $X \to \ell_\alpha^\pm + jj$	Right-handed neutrino decaying via gauge bosons
Leptonic	$X \to \ell^+\ell^-$ $X \to \ell^+\ell^- + \not{E}_{\mathrm{T}}$ $X \to \ell^\pm + \not{E}_{\mathrm{T}}$	SUSY: wino decaying to leptonic Z + neutralino
Flavoured leptonic	$X \to \ell_\alpha^+\ell_\beta^-(+\not{E}_{\mathrm{T}})$ $X \to \ell_\alpha^\pm + \not{E}_{\mathrm{T}}$	RPV SUSY: neutralino decaying to 2ℓ + neutrino

LLP Channels proposals (production * decay)

LLP channels of production x decay. We considered three separate cases:

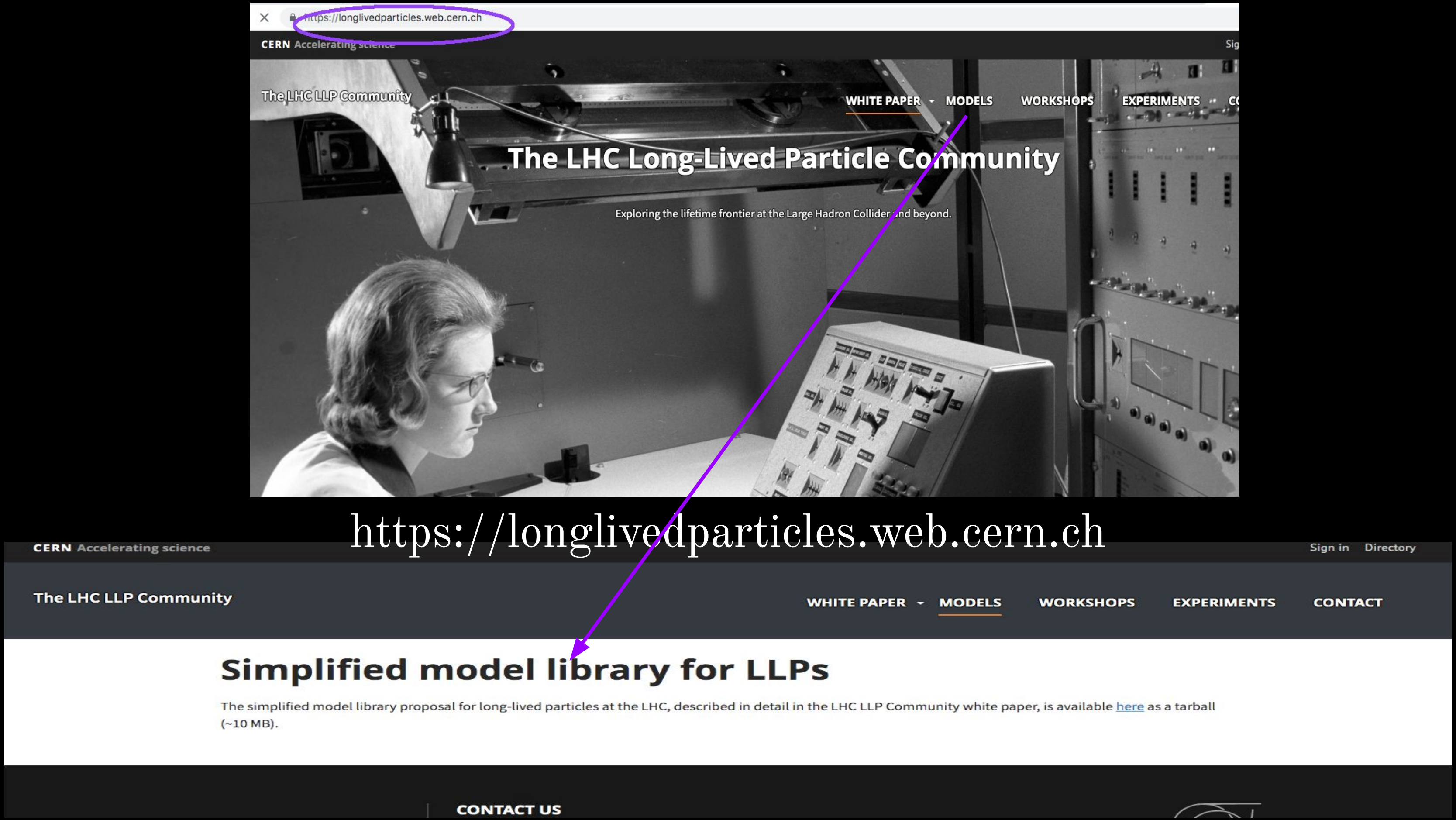
1) Neutral LLP
2) Electrically charged LLP
3) Colored LLP

Example: Neutral LLP Channels

LLP community whitepaper arXiv:1903.04497

Production \ Decay	$\gamma\gamma(+\text{inv.})$	$\gamma+\text{inv.}$	$jj(+\text{inv.})$	$jj\ell$	$\ell^+\ell^-(+\text{inv.})$	$\ell_\alpha^+\ell_{\beta\neq\alpha}^-(+\text{inv.})$
DPP: sneutrino pair	†	SUSY	SUSY	SUSY	SUSY	SUSY
HP: squark pair, $\tilde{q}\to jX$ or gluino pair $\tilde{g}\to jjX$	†	SUSY	SUSY	SUSY	SUSY	SUSY
HP: slepton pair, $\tilde{\ell}\to\ell X$ or chargino pair, $\tilde{\chi}\to WX$	†	SUSY	SUSY	SUSY	SUSY	SUSY
HIG: $h\to XX$ or $\to XX+\text{inv.}$	Higgs, DM*	†	Higgs, DM*	RHν	Higgs, DM* RHν*	RHν*
HIG: $h\to X+\text{inv.}$	DM*, RHν	†	DM*	RHν	DM*	†
RES: $Z(Z')\to XX$ or $\to XX+\text{inv.}$	Z', DM*	†	Z', DM*	RHν	Z', DM*	†
RES: $Z(Z')\to X+\text{inv.}$	DM	†	DM	RHν	DM	†
CC: $W(W')\to\ell X$	†	†	RHν*	RHν	RHν*	RHν*

Plan is to provide a LLP Simplified Model library with: descriptions, cards & instructions of how to simulate each channel https://longlivedparticles.web.cern.ch/



Going Back to our LLP chart: How can we understand what Nature looks like? From theory to experiment

Motivation

Dark Matter
Baryogenesis
Neutrino Masses
Naturalness

Theory

SUSY Multiple LLPs with SM gauge charges RPV, split SUSY
Higgs Portal LLPs predominantly coupled to the Higgs Hidden Valley
Gauge Portal New vector mediators can produce LLPs Z', dark photon
Dark Matter Non SUSY, hidden sector DM produced as final state at colliders EWK Multiplets, FIMP, SIMPs
RH Neutrinos RHnu masses in the GeV to TeV range can be LLP SM+N, Left-Right Symmetry

Phenomenology

LLPs strategies
Identify signatures
Model reinterpretation

Experiment

Implement and reconstruct those signatures
Hunt them in the Data
Experimental results

Long-lived Particle Community White Paper arXiv:1903.04497
MATHUSLA physics case arXiv:1806.07396

The need for Reinterpretation

Experiments use resources/manpower/cost/effort in creating a dedicated analysis. Can not cover all possibilities

Experimental results $<$ Theoretical models

How can we (theorists/phenomenologist) do an efficient and reliable reinterpretation of an experimental result to different BSM scenarios?

We need extensive information about analysis details !

Including cutflows, publicly available efficiencies, reliable LLP simulation outside the experiments. **Not** always **easy** due to the challenges in LLP searches

LLPs Reinterpretation Challenges

Prompt Searches

Signal Generation
Selection Cuts
Signal Region definition/cuts
Trigger efficiencies
Validation

Standard Tools available for all these (i.e DELPHES, MadAnalysis, CheckMate). Processes are streamlined.

LLP searches

Signal Generation
Selection Cuts
Signal Region definition/cuts
Trigger efficiencies
Validation
Displacement in EG
Tracking and Vertexing efficiencies
Detector effects in displacement/timing

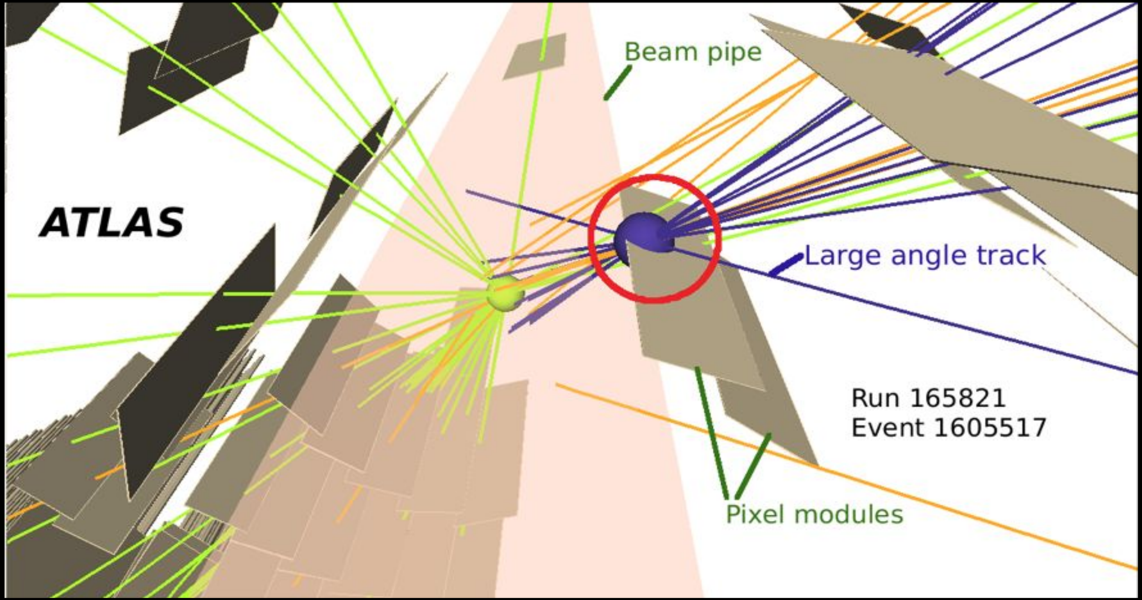
Not much information. No standard tools nor way of doing things.

Risk of dangerous extrapolations. Validation is KEY!

Standard objects (jets electrons, muons, tracks) are not so standard anymore if they are/come from a LLP. Reconstruction efficiencies have a strong dependence on LLP decay position/boost, which are hard to model within custom/publicly available simulation tools

Example 1: ATLAS Multitrack Displaced Vertex Search [arXiv:1504.05162] Phys. Rev. D 92, 072004 (2015)

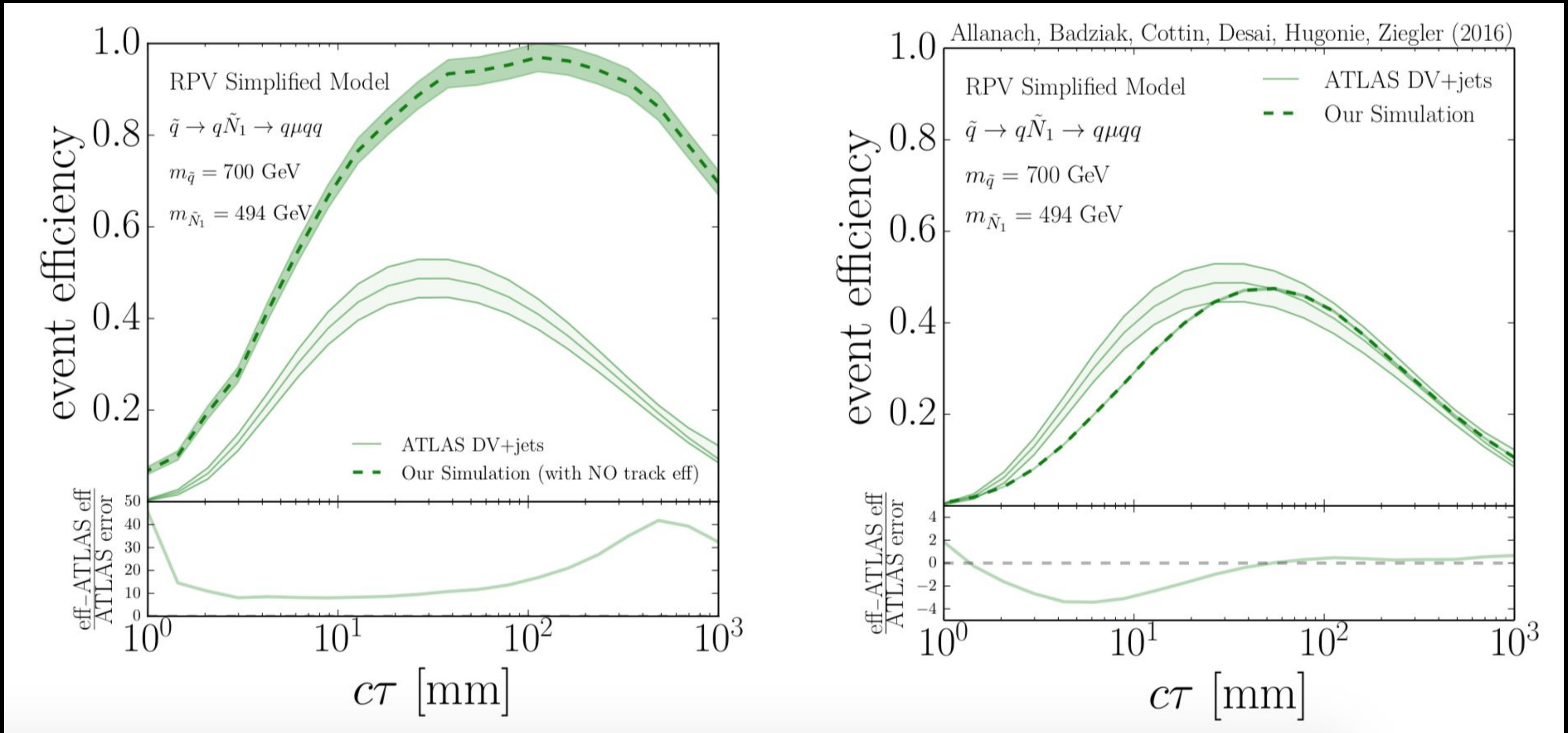
Standard ATLAS tracking is run again with looser cuts to gain efficiency for high-d0 tracks



Source: ATLAS Event Display arXiv:1109.2242

Recasting ATLAS Displaced Vertex Search [arXiv:1504.05162] Phys. Rev. D 92, 072004 (2015)

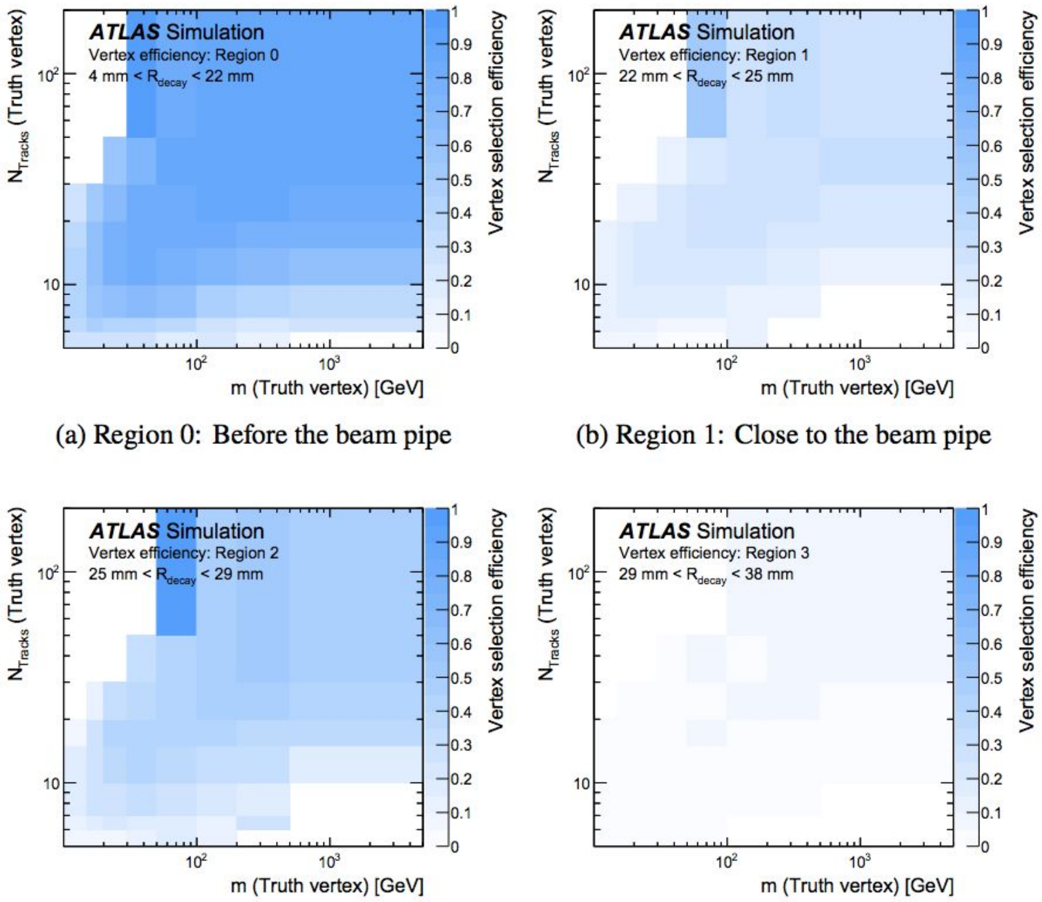
8 TeV Validation : Not much recasting info. Ad hoc track efficiency function defined in [arXiv:1606.03099] Eur.Phys.J. C76 (2016) B. C. Allanach, M. Badziak, G. Cottin, N. Desai, C. Hugonie and R. Ziegler



Recasting ATLAS Displaced Vertex Search [arXiv:1504.05162] Phys. Rev. D 92, 072004 (2015)

Since then, public ATLAS efficiency grids at 13 TeV to model detector response to DVs.

Can be applied to truth-level MC (nTrk, mDV, rDV)



(a) Region 0: Before the beam pipe

(b) Region 1: Close to the beam pipe

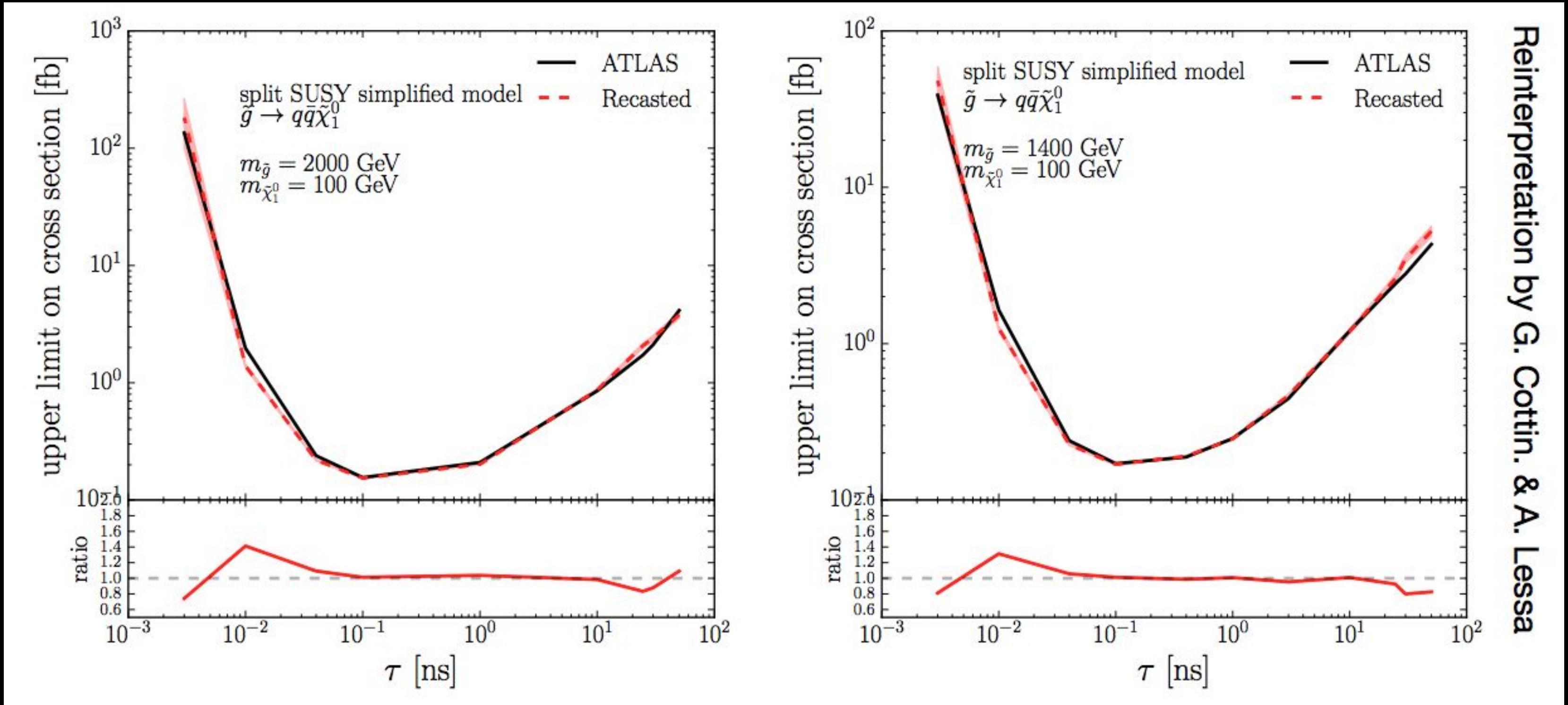
(c) Region 2: Before the IBL

(d) Region 3: Close to the IBL

Recasting ATLAS Displaced Vertex Search [arXiv:1504.05162] Phys. Rev. D 92, 072004 (2015)

13 TeV Validation : Limits Looking MUCH alike for Les Houches 2018 !!!

[1803.10379] C17-06-05.2 G. Cottin, N. Desai, J. Heisig and A. Lessa



Example 2: CMS Displaced Vertex Search plus jets [arXiv:1808.03078] Phys. Rev. D 98 (2018)

13 TeV Validation : CMS provides a prescription for recasting !

10 Extending the search to other signal models

This search for displaced vertices applies to other types of long-lived particles decaying to multiple jets. Here we present a generator-level selection that can be used to reinterpret the results of our analysis. For signal models in which there are two long-lived particles, this generator-level selection approximately replicates the reconstruction-level efficiency. The selection is based on the number and momenta of generated jets in the event, the displacements of the long-lived particles, and the momenta of their daughter particles. The generated jets are those clustered from all final-state particles except neutrinos, using the anti-k_T algorithm with a distance parameter of 0.4, but are rejected if the fraction of energy from electrons is greater than 0.9 or if the fraction of energy from muons is greater than 0.8. The daughter particles are

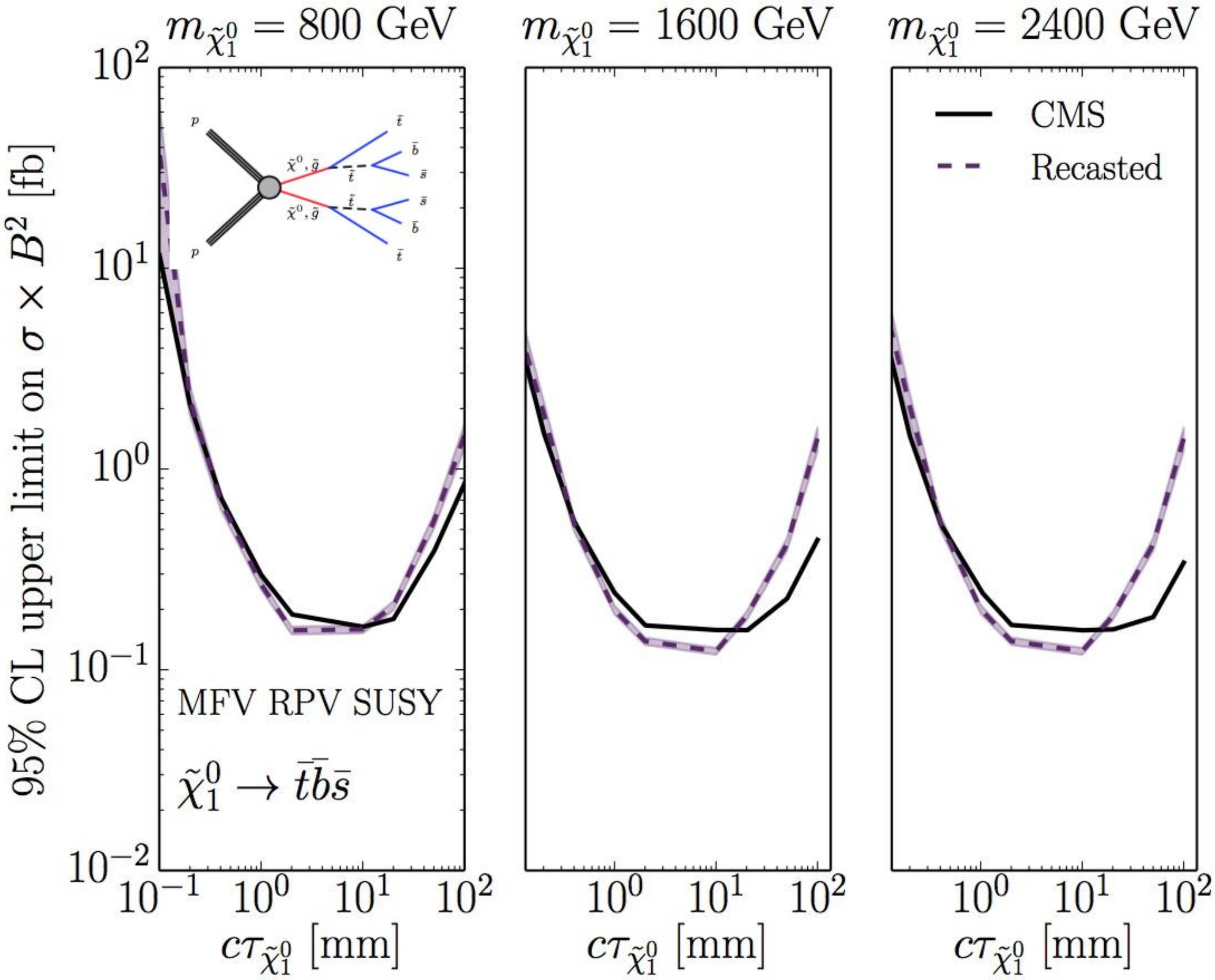
Example 2: CMS Displaced Vertex Search plus jets [arXiv:1808.03078] Phys. Rev. D 98 (2018)

13 TeV Validation : CMS provides a prescription for recasting !

Reinterpretation in Z' models : C.-W. Chiang, G.Cottin, A. Das, S. Mandal [arXiv:1908.09838]

Trigger	$H_T > 1000$ GeV
Jet selection	At least 4 jets with $p_T > 20$ GeV and $\|\eta\| < 2.5$
DV region	2 DVs within 0.1 mm $< r_{DV} <$ 20 mm and $d_{VV} > 0.4$ mm
DV selection	Made from tracks with $\|d_0\| \geq 0.1$ mm, $p_T > 20$ GeV and $\|\eta\| < 2.5$.
	$\sum p_T \geq 350$ GeV, correcting for b quarks.

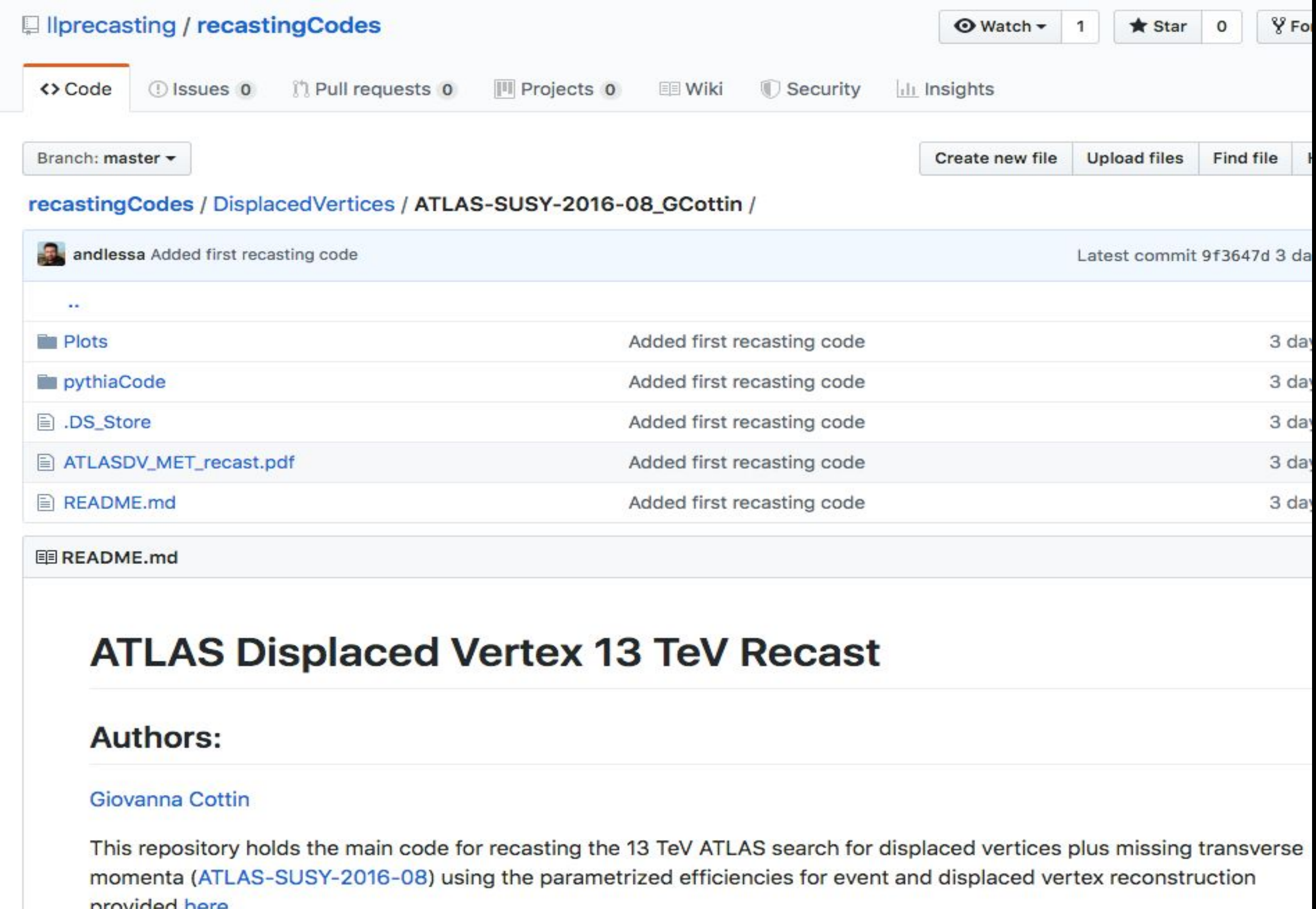
TABLE III. Cuts for the CMS 2DV + jets search following the reinterpretation procedure in [61].



[arXiv:1908.09838]

Going Open : You can find original recast from Example 1 on our LLP gitHub !

More to come !



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recastingCodes / DisplacedVertices / ATLAS-SUSY-2016-08_GCottin /

andlessa Added first recasting code — Latest commit 9f3647d 3 da

..		
Plots	Added first recasting code	3 day
pythiaCode	Added first recasting code	3 day
.DS_Store	Added first recasting code	3 day
ATLASDV_MET_recast.pdf	Added first recasting code	3 day
README.md	Added first recasting code	3 day

README.md

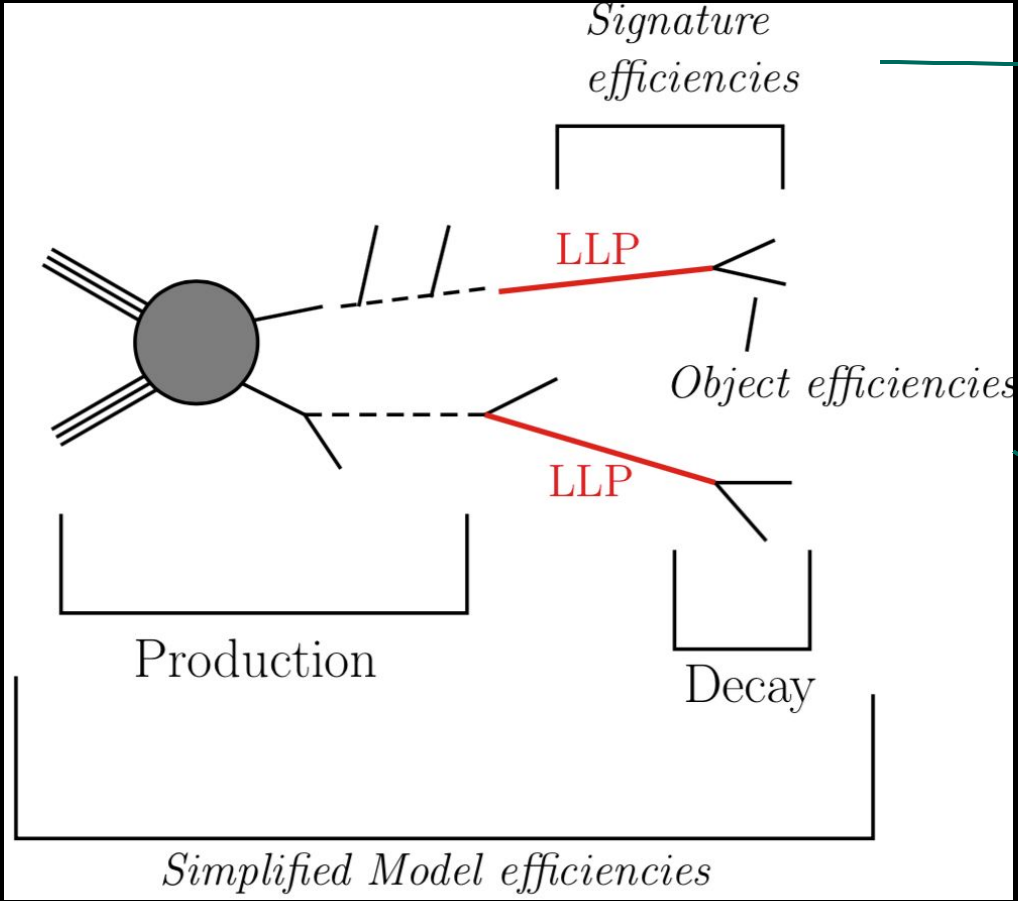
ATLAS Displaced Vertex 13 TeV Recast

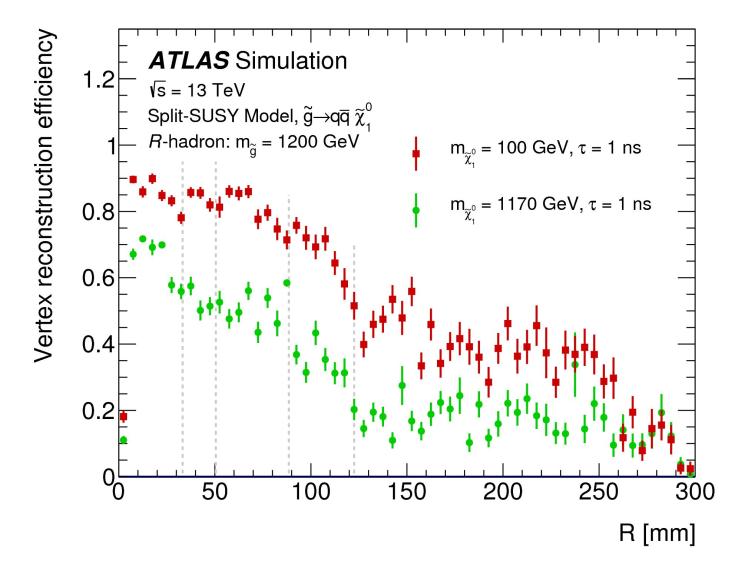
Authors:

Giovanna Cottin

This repository holds the main code for recasting the 13 TeV ATLAS search for displaced vertices plus missing transverse momenta (ATLAS-SUSY-2016-08) using the parametrized efficiencies for event and displaced vertex reconstruction provided here

Lessons Learned: Different levels of Information

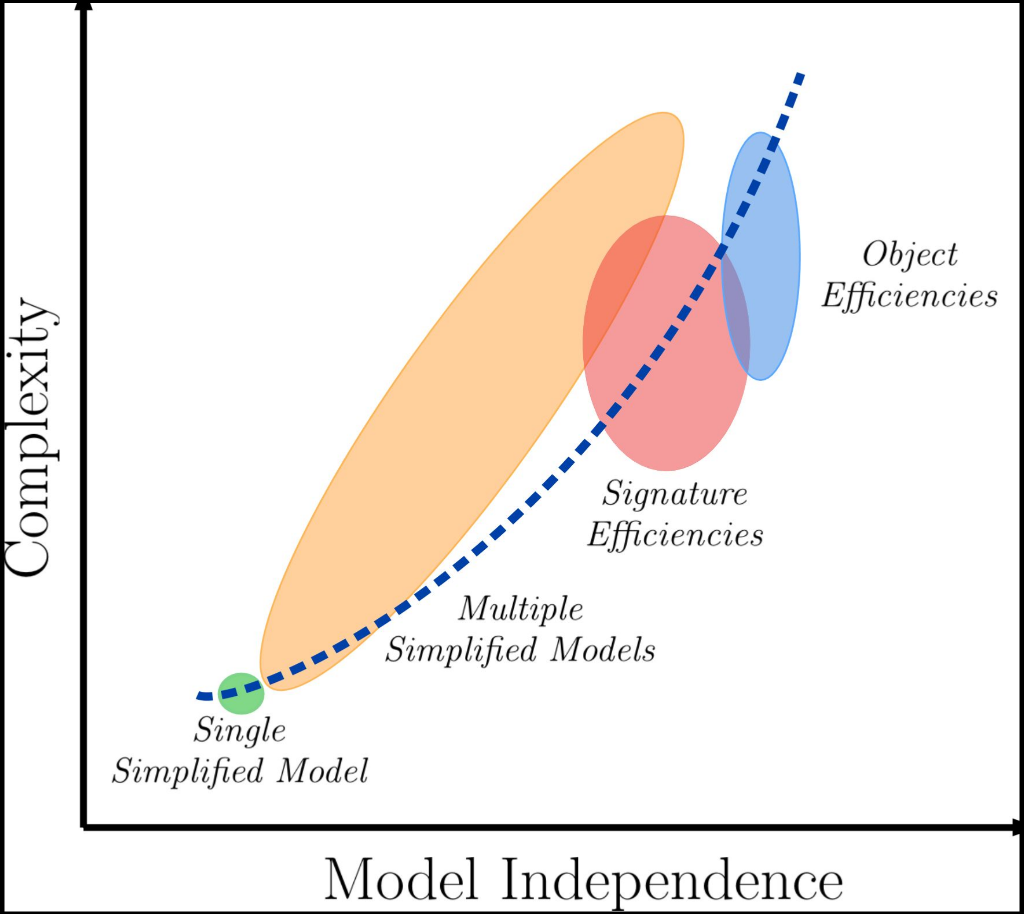




$$\varepsilon_{\text{trk}} = 0.5 \times \left(1 - \exp\left(\frac{-p_T}{4.0\ \text{GeV}}\right)\right) \times \exp\left(\frac{-z_{\text{DV}}}{270\ \text{mm}}\right) \times \max\left(-0.0022 \times \frac{r_{\text{DV}}}{1\ \text{mm}} + 0.8, 0\right),$$

LLP community whitepaper arXiv:1903.04497

Simplified models can also help with reinterpretation !



LLP community whitepaper
arXiv:1903.04497

Recommendations for the presentation of Search Results: Detailed proposal in our White Paper !

LLP community whitepaper arXiv:1903.04497

6.8 *Our Proposals for the Presentation of Results*

Here we summarize the recommendations for the presentation of searches involving long-lived particles. These recommendations follow from the detailed examples presented in Sections 6.3 and 6.4.

Our primary recommendation is that the experiments provide as detailed information as possible to make a general recasting feasible. We therefore encourage the experiments to:

A.1. Provide LLP reconstruction and selection efficiencies at the signature or object level. Although the parametrization of efficiencies is strongly analysis dependent, it is advantageous if they are given as a function of model-independent variables (such as functions of displaced vertex d_0, p_T, η, etc.), so they do not rely on a specific LLP decay or production mode;

A.2. Present results for at least two distinct benchmark models, with different event topologies, since it greatly helps to validate the recasting. For clarity, the input cards for the benchmark points should also be provided;

A.3. Present cut-flow tables, for both the signal benchmarks and the background, since these are very useful for validating the recasting;

A.4. When an analysis is superseded, differences and commonalities with previous versions of the same analysis should be made clear, especially if the amount of information presented in both analyses differs. The understanding as the extent to which the information presented in an old version can be used directly in a later version greatly helps the recasting procedure, and also highlights ways in which the new search gains or loses sensitivity relative to the superseded analysis;

A.5. Provide all this material in numerical form, preferably on HEPdata, or on the collaboration wiki page. A very useful resource we also highly encourage is a truth-code snippet illustrating the event and object selections, such as the one from the ATLAS disappearing-track search [211] provided in HEPdata under "Common Resources".

When the object- or signature-level efficiency maps are not feasible, providing efficiencies for an extensive, diverse array of simplified models can be useful for reinterpretation. Concerning simplified-model results, we recommend that the experiments:

B.1. Provide signal efficiencies (acceptance times efficiency) for

LLP Summary and future roadmap

LLPs are very well motivated ! Are ubiquitous in most BSM frameworks

We have designed a *first systematic* LLP search program with a simplified models proposal. Many things not considered can still be interesting! (i.e higher multiplicities, expand LLP decays to three-body, separate jets into heavy and light flavour https://higgs.ph.ed.ac.uk/workshops/long-lived-particles-and-the-third-generation/)

We have provided extensive recommendations to better reinterpret LHC LLP searches

For more details and studies (including hardware opportunities and gaps in current coverage), see our community whitepaper [arXiv:1903.04497] !

LLP Summary and future roadmap

Searching for Long-Lived Particles at the LHC: Sixth Workshop of the LHC LLP Community (Ghent, 27-29 Nov. 2019)

Long-live particle physics !

Mapping the future of BSM physics today