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Exotic collider probes of dark matter

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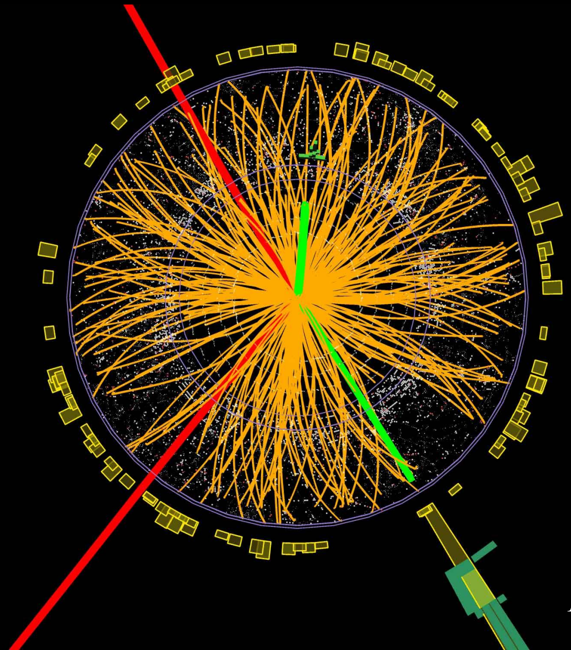
HEP Seminar, UTFSM
January 2021

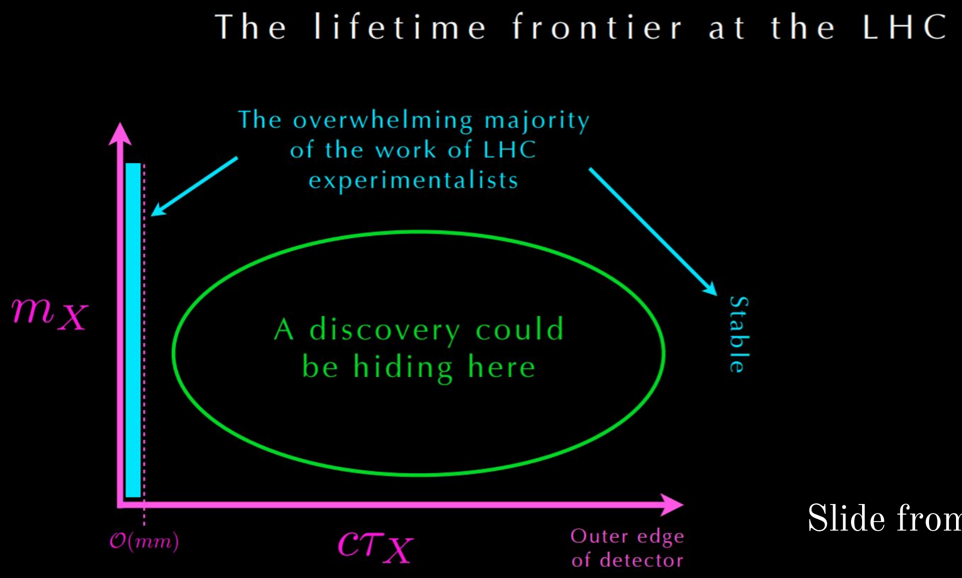


ATLAS@CERN

Where may the new physics be hiding @ LHC?

In exotic decay patterns (long-lived particle signatures/displaced decays) → We can design new searches based on lifetime (to cover more model and signature space)

See J. Alimena et al, *Searching for Long-Lived Particles beyond the Standard Model at the Large Hadron Collider*, arXiv:1903.04497



Slide from J. Beacham @ LLP Workshop

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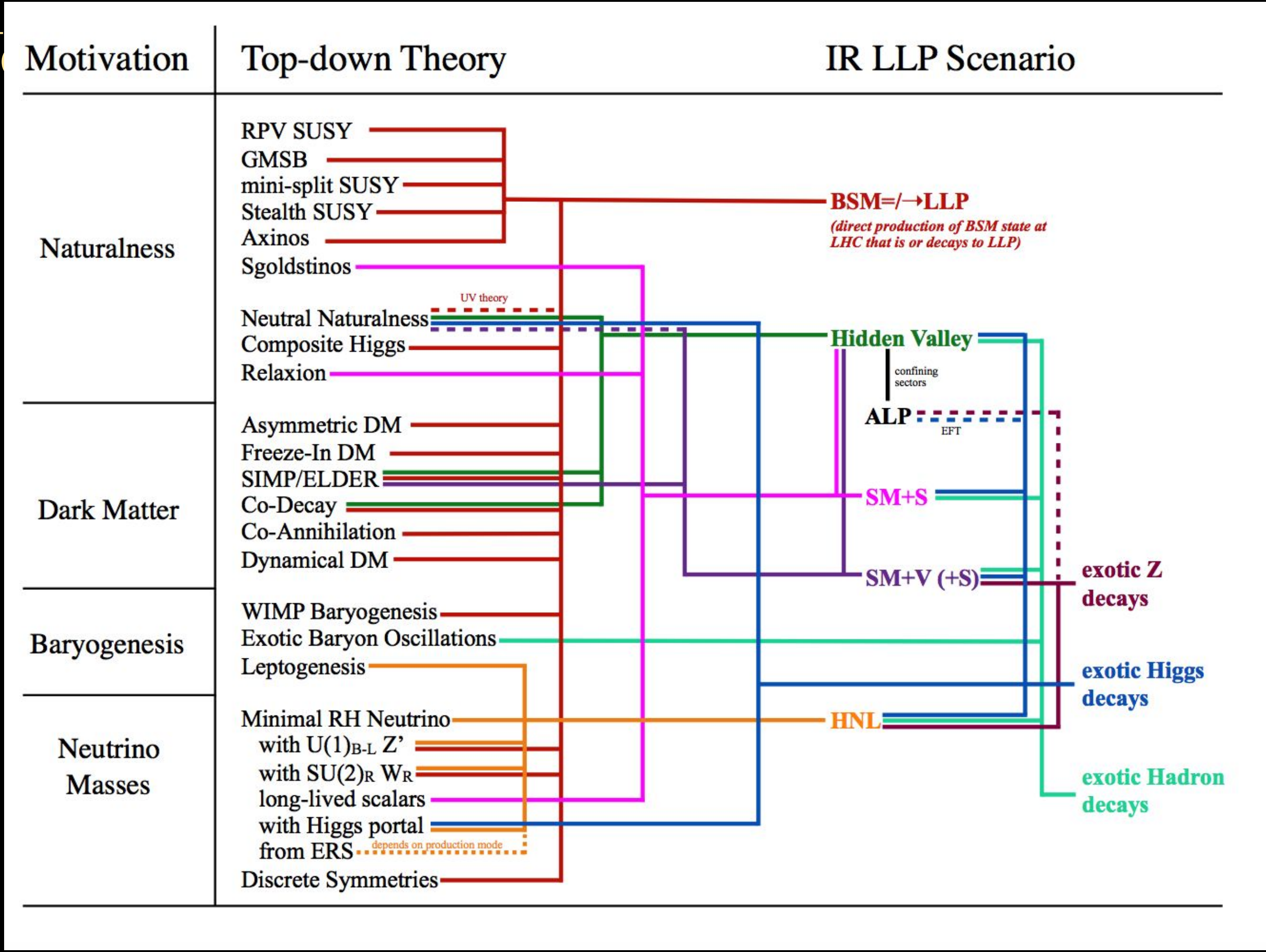

Source: MATHUSLA physics case arXiv:1806.07396

LLP Efforts Worldwide!

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.

Editors:
Juliette Alimena(1) (Experimental Coverage, Backgrounds, Upgrades), James Beacham(2) (Document Editor, Simplified Models), Martino Borsato(3) (Backgrounds, Upgrades), Yangyang Cheng(4) (Upgrades), Xabier Cid Vidal(5) (Experimental Coverage), Giovanna Cottin(6) (Simplified Models, Reinterpretations), Albert De Roeck(7) (Experimental Coverage), David Curtin(9) (Simplified Models), Jared A. Evans(10) (Simplifie Simon Knapen(11) (Dark Showers), Sabine Kraml(12) (Reinterpre Zhen Liu(14) (Simplified Models, Backgrounds, Reinterpretations) Michael J. Ramsey-Musolf(16,126) (Simplified Models), Heather R Jessie Shelton(18) (Simplified Models, Dark Showers), Brian Shu Simplified Models, Simplified Models Library), Monica Verducci(2 (Experimental Coverage)

LLP Community white-paper, arXiv:1903.04497, J.Phys.G 47 (2020) 9, 090501

SnowMass2021

WELCOME PAGE
ANNOUNCEMENTS
SNOWMASS CALENDAR
ETHICS GUIDELINES
- Organization
SNOWMASS ADVISORY GROUP
SNOWMASS STEERING GROUP
FRONTIER CONVENERS
APS DPF SNOWMASS PAGE
SNOWMASS EARLY CAREER
- Snowmass Frontiers
ENERGY FRONTIER
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COSMIC FRONTIER
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- Community Contributions

EF09 - BSM: More general explorations

Table of Contents
- EF09 - BSM: More general explorations
  - Group Topics
  - Mee
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Conveners	Tulika Bose, Zhen Liu, Simone Pagan Griso (more contac
Mailing-list	SNOWMASS-EF-09-BSM_GENERIC@FNAL.GOV (inst
Slack channel	ef09-bsm_generic (instructions)
Next Event	TBA
Expression of Interests (EOI) form	https://forms.gle/1freqMHfTjAobga86
Current EOI	List of Active Proposals agreed to share, comments wel

This topical group aims to study the sensitivity of Beyond Standard Model (BSM) phenomena for fut the energy frontier. Particular emphasis is given to signatures that appear in a large variety of BSM e

This TWiki page collects useful information on organization, topics, and technical details, as we see u community. Please check for updates often and subscribe to our mailing list (see above) to be kept up

Group Topics

An initial list of topics to be covered by this topical group are:

- New Fermions, e.g., Top partners, Excited Quarks/Leptons, Sterile Neutrinos
- New Bosons, e.g., W', Z', diboson-resonances
- Dark/Hidden sectors, e.g., ALP, dark photons
- Long-live particle signatures
- BSM interplay with EFT

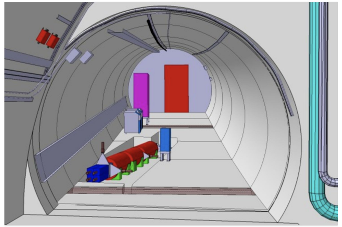
New dedicated Experiments !

ABOUT NEWS

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

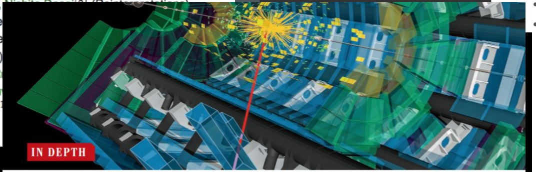


A 3D picture of the planned FASER detector as seen in the TI12 tunnel. The detector is precisely aligned with the collision axis in ATLAS, 480 m away from the collision point. (Image: FASER/CERN)

Geneva. Today, the CERN Research Board approved a new experiment designed to look for light and weakly

Sign in

UBLICATIONS EVENTS NEWSLET



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: kinks 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

LLPs in *Science*, May 2019

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-liv and theorists to physics with unc LLP LHC Commu with the relevant endorsement of meetings, typica Community. The

Dark Matter WG
- WG documents
- WG Meetings

Electroweak WG

Searching for long-lived particles at the LHC and beyond: Eighth workshop of the LHC LLP Community

16 Nov 2020, 12:00 → 20 Nov 2020, 19:00 Europe/Zurich

Virtually, worldwide

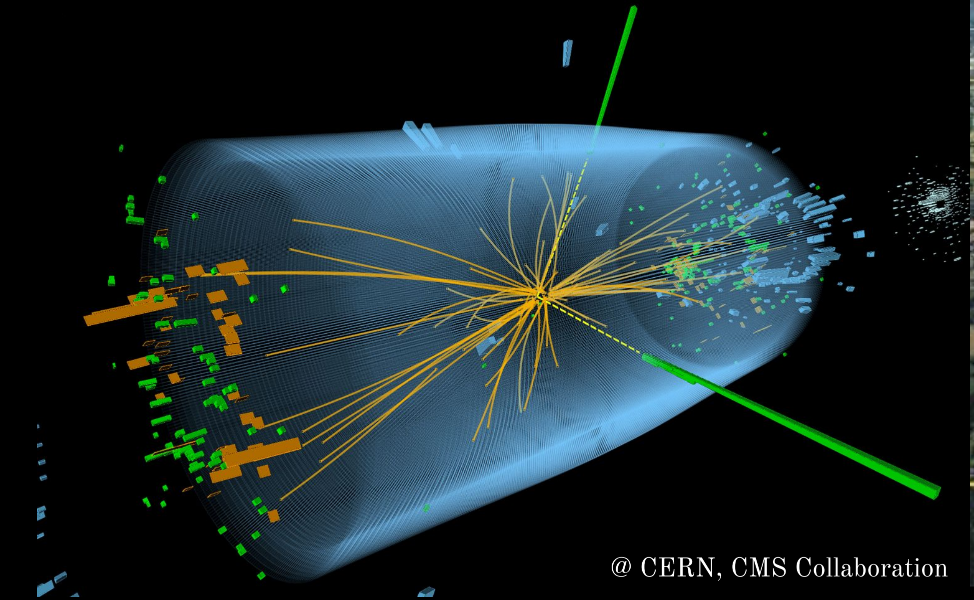
Albert De Roeck (CERN), Carlos Vazquez Sierra (Nikhef National institute for subatomic physics (NL)), Federico Leo Redi (EPFL - Ecole Polytechnique Federale Lausanne (CH)), Giovanna Cottin (Universidad Adolfo Ibañez), James Beacham (Duke University (US)), Karri Folan Di Petrillo (Fermi National Accelerator Lab. (US)), Katherine Pachal (Duke University (US)), Matthew Daniel Citron (Univ. of California Santa Barbara (US)), Nishita Desai (Tata Institute of Fundamental Research), Rebeca Gonzalez Suarez (Uppsala University (SE))

LLP Workshops !

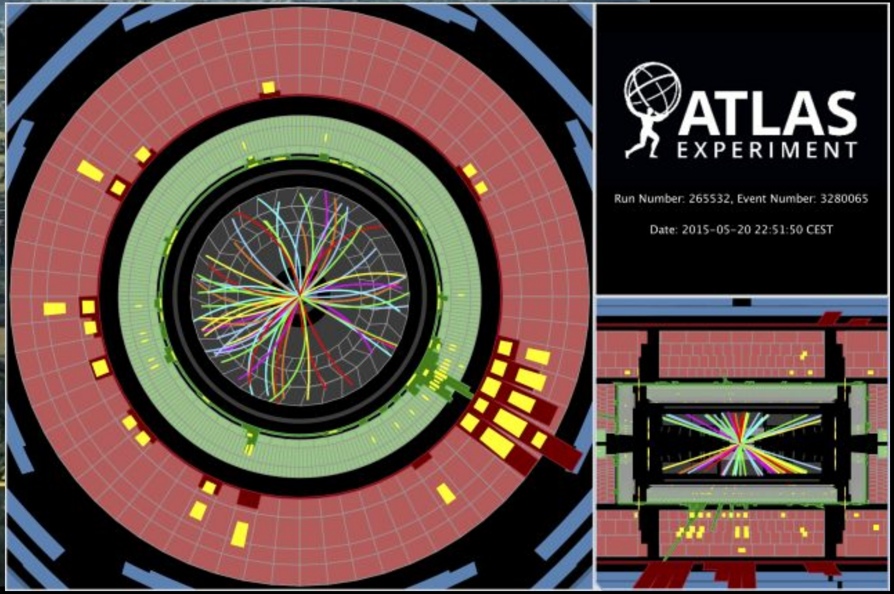
Description

To understand the Universe as seen today, new physics is needed. We are looking for it @ the

Large Hadron Collider at CERN



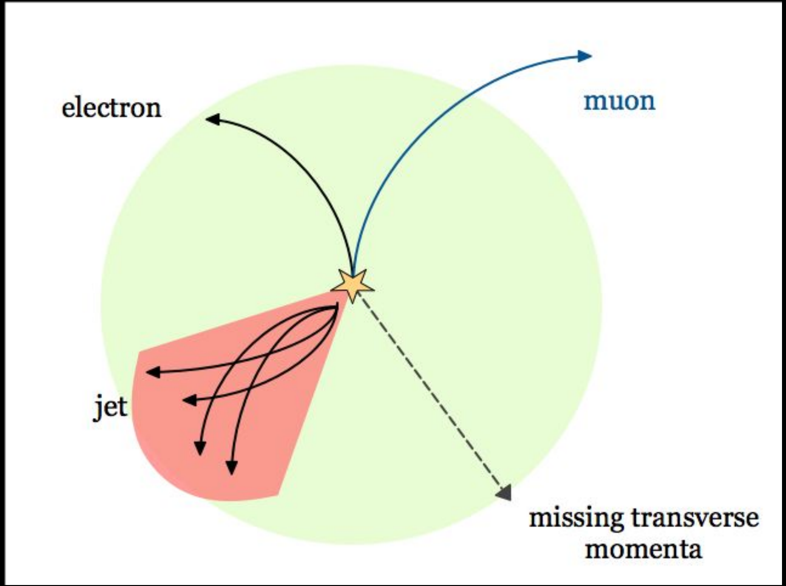
@ CERN, CMS Collaboration



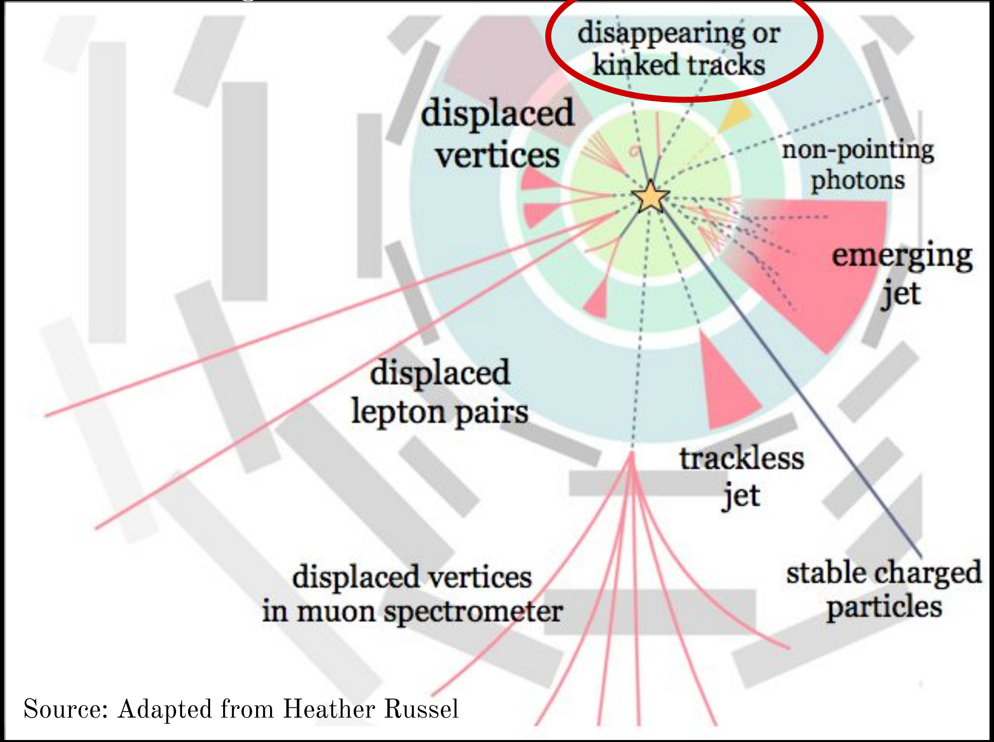
Should carefully extend our physics program to look everywhere!

Motivated by dark matter

Standard Prompt Signatures



Exotic LLP Signatures



Source: Adapted from Heather Russel

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

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

Heavy 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
See also MATHUSLA physics case motivating models arXiv:1806.07396

The r

Phenomenology

Theory ⟷ Experiment

Expe … ed
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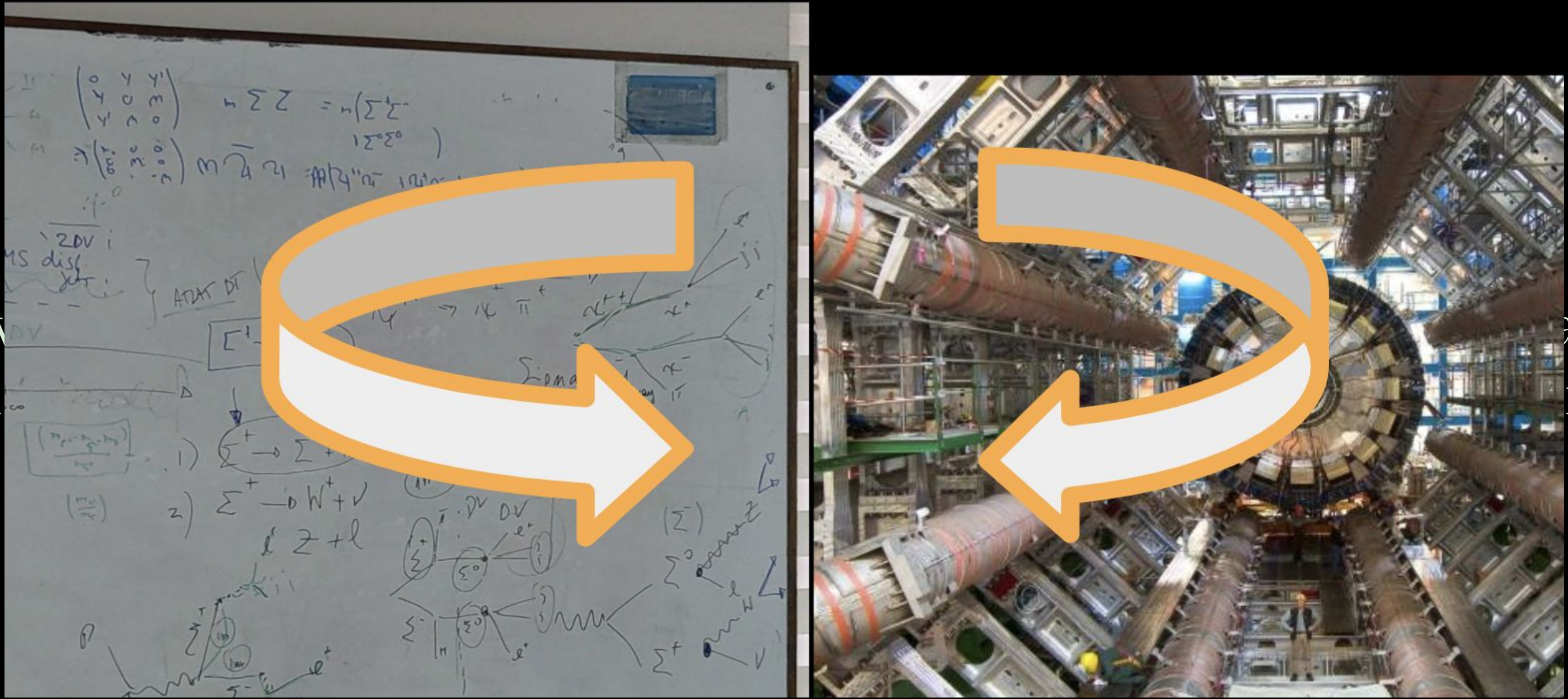


We need extensive information about analysis details !

LLPs Reinterpretation Challenges

6. Reinterpretation and recommendations for the presentation of search results

Chapter editors: Giovanna Cottin, Nishita Desai, Sabine Kraml, Andre Lessa, Zhen Liu
Contributors: Juliette Alimena, Will Buttinger, Eric Conte, Yanou Cui, Jared Evans, Benjamin Fuks, Lukas Heinrich, Jan Heisig, Gavin Hesketh, David Michael Morse, Michael Ramsey-Musolf, Ennio Salvioni, Michele Selvaggi, Brian Shuve, Yuhsin Tsai

6.1. Introduction

Models and scenarios with LLPs have seen an enormous rise in interest in recent years. They include supersymmetric scenarios with almost mass-degenerate lightest states [63, 65], highly split spectra [113, 475], very weakly interacting LSPs like gravitinos or axinos [476, 477], or *R*-parity violation [55, 110, 111], as well as equivalent scenarios in other SM extensions (e.g. extra-dimensional models) with new SM gauge-charged particles. More recent ideas include models with feebly interacting DM [146] (supersymmetric or not), asymmetric DM [478],

124

LLP White Paper arXiv:1903.04497

<u>Prompt Searches</u>

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.

<u>LLP searches</u>

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!

Using Long-Lived Particles @ LHC to shed light on

Dark Matter

Dark matter coming from the decay of a long-lived particle with a disappearing track signature

Based on C.-W. Chiang, G. Cottin, Y. Du, K. Fuyuto, M.J. Ramsey-Musolf

[arXiv: 2003.07867], JHEP accepted

Dark Matter

Triplet Scalar DM Model

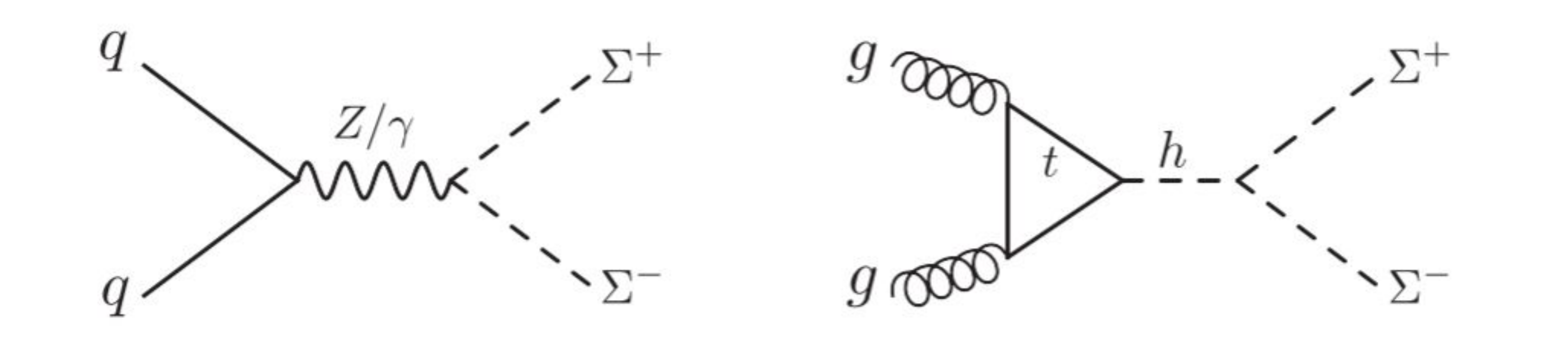
M. Cirelli, N. Fornengo and A. Strumia,, Nucl. Phys. B753 (2006) 178–194
P. Fileviez Perez, H. H. Patel, M. Ramsey-Musolf and K. Wang, Phys. Rev. D79 (2009) 055024

$$\Sigma = \frac{1}{2}\begin{pmatrix} \Sigma^0 & \sqrt{2}\Sigma^+ \\ \sqrt{2}\Sigma^- & -\Sigma^0 \end{pmatrix}$$

New interactions with the Higgs Boson ! C.-W. Chiang, G. Cottin, Y. Du, K. Fuyuto, M.J. Ramsey-Musolf https://arxiv.org/abs/2003.07867

$$V\left(H,\Sigma\right) = -\mu^2 H^\dagger H + \lambda_0 \left(H^\dagger H\right)^2 - \frac{1}{2}\mu_\Sigma^2 F + \frac{b_4}{4}F^2 + \frac{a_2}{2}H^\dagger H F,$$

$$F = \left(\Sigma^0\right)^2 + 2\Sigma^+\Sigma^-.$$



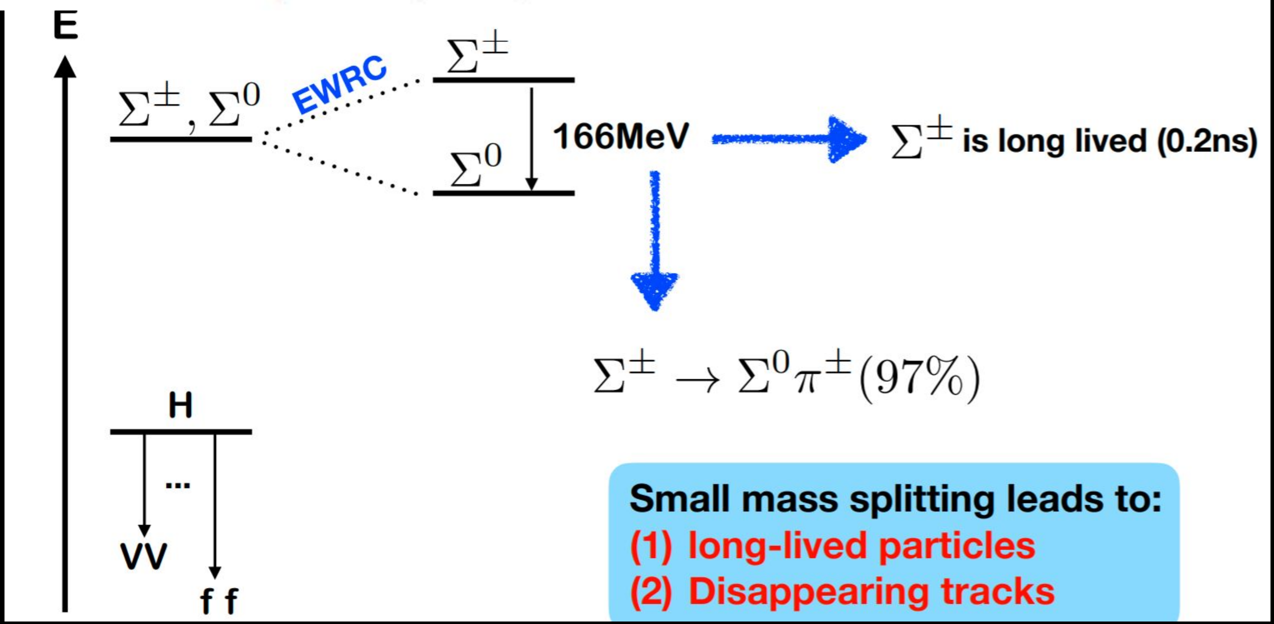
Dark Matter

Triplet Scalar DM Model C.-W. Chiang, G. Cottin, Y. Du, K. Fuyuto, M.J. Ramsey-Musolf https://arxiv.org/abs/2003.07867

$$\Gamma\left(\Sigma^{\pm} \to \Sigma^{0}\pi\ \right) = \frac{2G_F^2}{\pi} f_\pi^2 V_{ud}^2 (\Delta m)^3 \sqrt{1 - \frac{m_\pi^2}{(\Delta m)^2}}$$

Slide from Yong Du @LLP Workshop

$$\Sigma = \frac{1}{2}\begin{pmatrix} \Sigma^0 & \sqrt{2}\Sigma^+ \\ \sqrt{2}\Sigma^- & -\Sigma^0 \end{pmatrix}$$



Recent DM DT studies in:

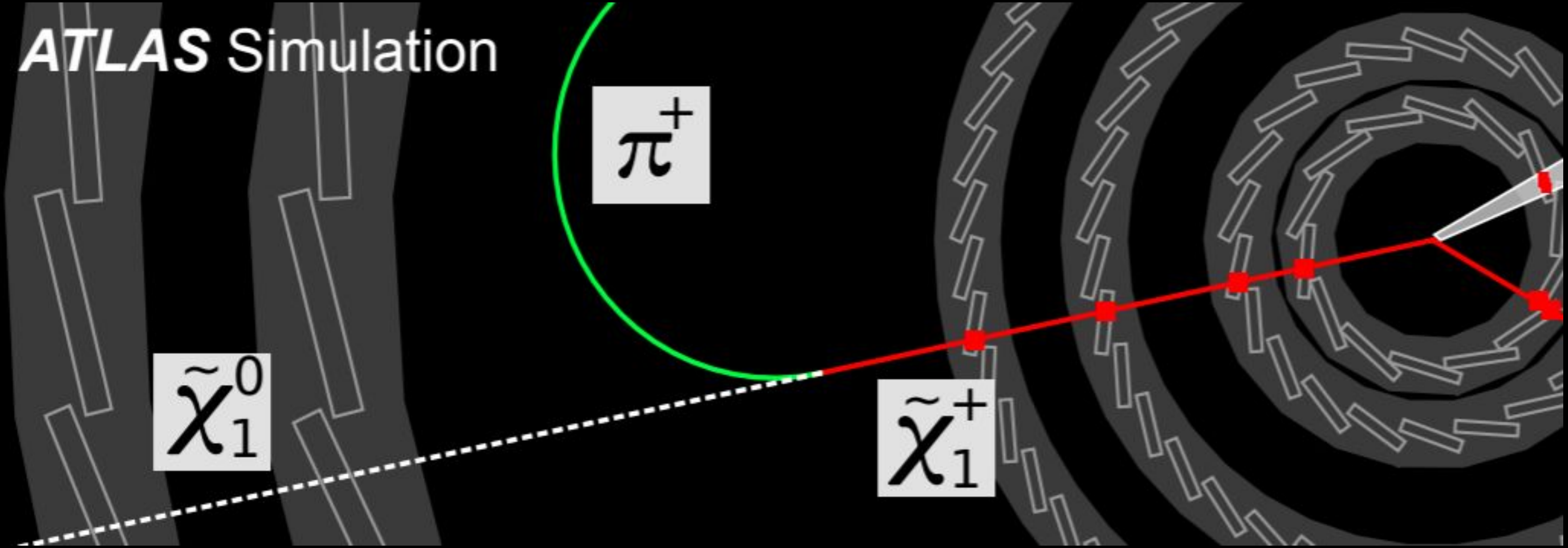
A. Belyaev, S. Prestel, F. Rojas-Abbate, J. Zurita arXiv:2008.08581

N. F. Bell, M. J. Dolan, L. S. Friedrich, M. J. Ramsey-Musolf, R. Volkas, arXiv:2001.05335

See also our LLP whitepaper, for more DM models with this exotic decay pattern! arXiv:1903.04497

Experimental Strategy : Search for a disappearing track:

https://arxiv.org/pdf/1712.02118.pdf



Analysis Recast: Validation using AMSB model & efficiency map

Validation is KEY!

The following analysis selection criteria are imposed:

- Trigger : $\not{p}_T > 140\,\mathrm{GeV}$
- Lepton veto : no electrons or muons

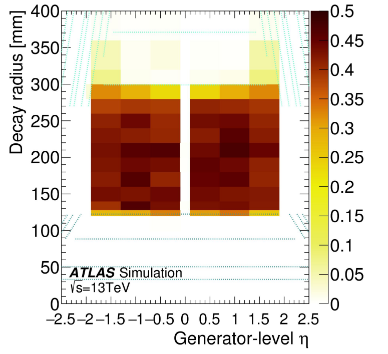
- Jet $p_T/\Delta\phi$: at least one jet with $p_T > 140\,\mathrm{GeV}$, and $\Delta\phi$ between the $\not{p}_T$ vector and each of the up to four hardest jets with $p_T > 50\,\mathrm{GeV}$ to be bigger than 1.0

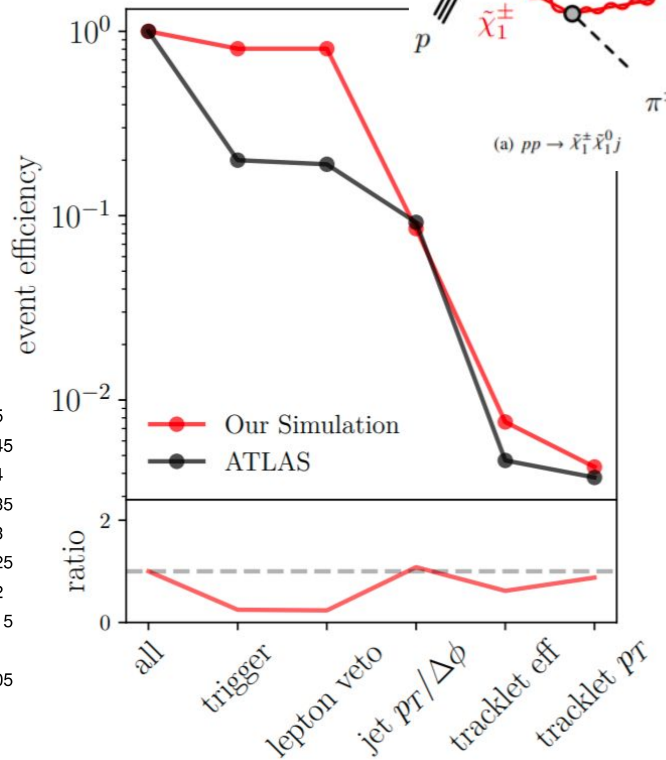
In what follows, we use "overall event level efficiency" to refer to the efficiency after these selection cuts. On top of these event selection requirements, we correct for detector effects and resolutions by multiplying the overall event level efficiency with the event efficiency provided by ATLAS in Table 2 of [34].[5]

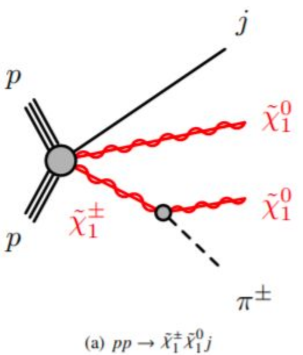
Then we proceed to select tracklets and require the following:

- Tracklet selection : at least one tracklet (generator-level chargino) with :
  - $p_T > 20\,\mathrm{GeV}$ and $0.1 < |\eta| < 1.9$
  - $122.5\,\mathrm{mm} <$ decay position $< 295\,\mathrm{mm}$
  - ΔR distance between the tracklet and each of the up to four highest$-p_T$ je with $p_T > 50\,\mathrm{GeV}$ to be bigger than 0.4
  - we apply the tracklet acceptance $\times$ efficiency map[6] provided by ATLAS, whic is based on the decay position and η. This is applied to selected tracklets passi the above selections.
- Tracklet p_T : Select tracklets with $p_T > 100\,\mathrm{GeV}$.

1712.02118







2003.07867

Analysis Recast: Validation using AMSB model & efficiency

LLPrecasting

llp-recasting@googlegroups.com

Repositories 1 | Packages | People 5 | Teams 1

Find a repository... | Type: All

recastingCodes

A collection of public codes for recasting long-lived particle searches

Jupyter Notebook 5 2 0 0 Updated on 11 Dec 2020

LLP Recasting Repository

This repository holds example codes for recasting long-lived particle (LLP) searches. The code authors and repository maintainers are not responsible for how the code is used and the user should use discretion when applying it to new models.

Adding your recasting code

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

Repository Structure

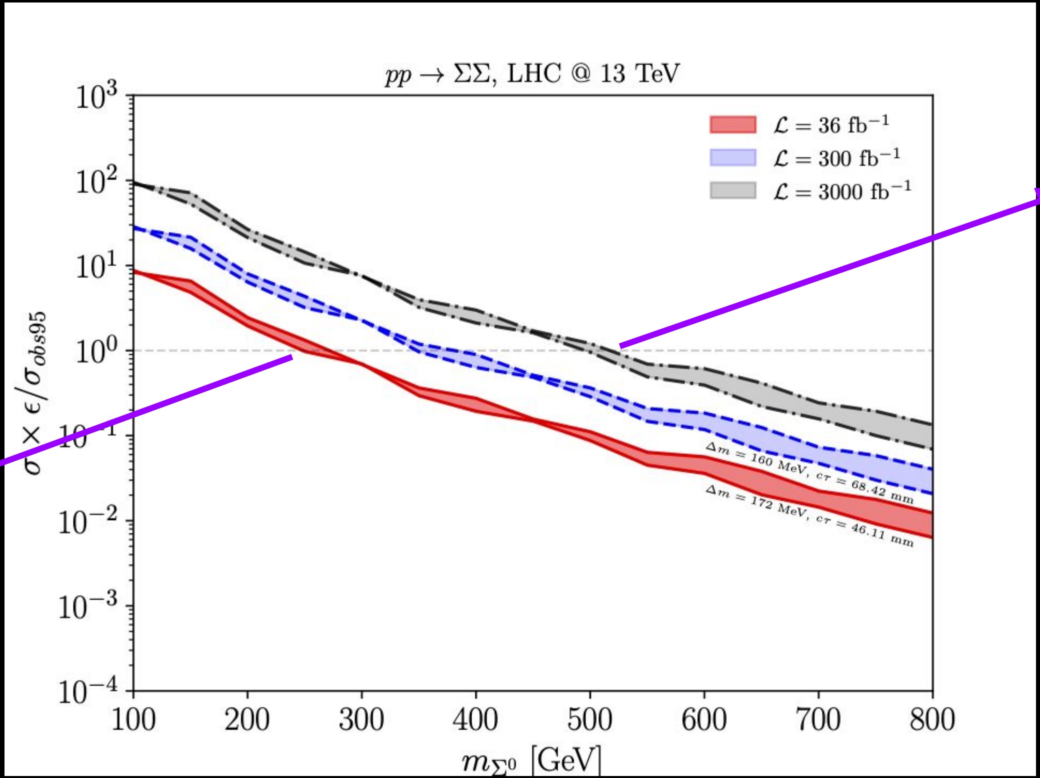
The repository folder structure is organized according to the type of LLP signature and the corresponding analysis and authors:

- 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

People 5

You can find original search recast on our LLP gitHub !

Scalar Triplet Dark Matter Model: LHC Exclusion



HL-LHC*: mΣ > 520 GeV

assumes

$\sigma_{\text{obs95}} \propto 1/\sqrt{\mathcal{L}}$

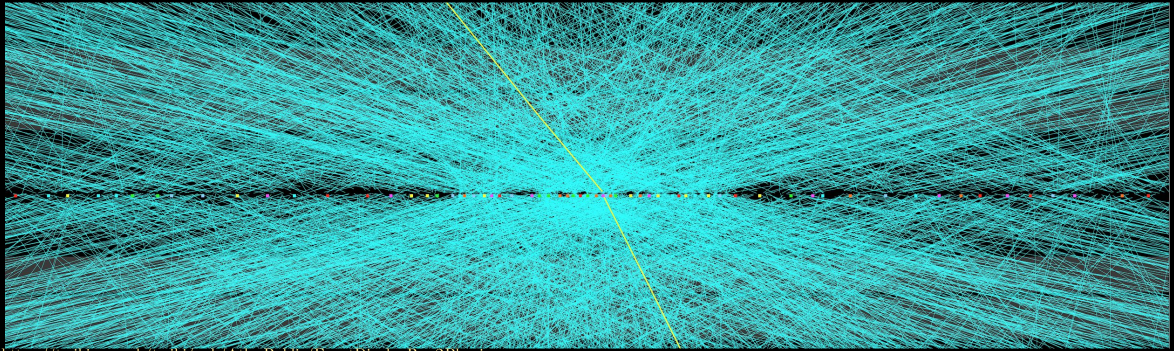
Current*: mΣ > 275 GeV

* Assumes Δ mΣ = 160 MeV

2003.07867

$S/\Delta B$ with $\Delta B = \sqrt{B + \delta B}$ and $\delta B = 0.3B$

Scalar Triplet Dark Matter Model: Future 100 TeV Collider (FCC-hh)



https://twiki.cern.ch/twiki/pub/AtlasPublic/EventDisplayRun2Physics

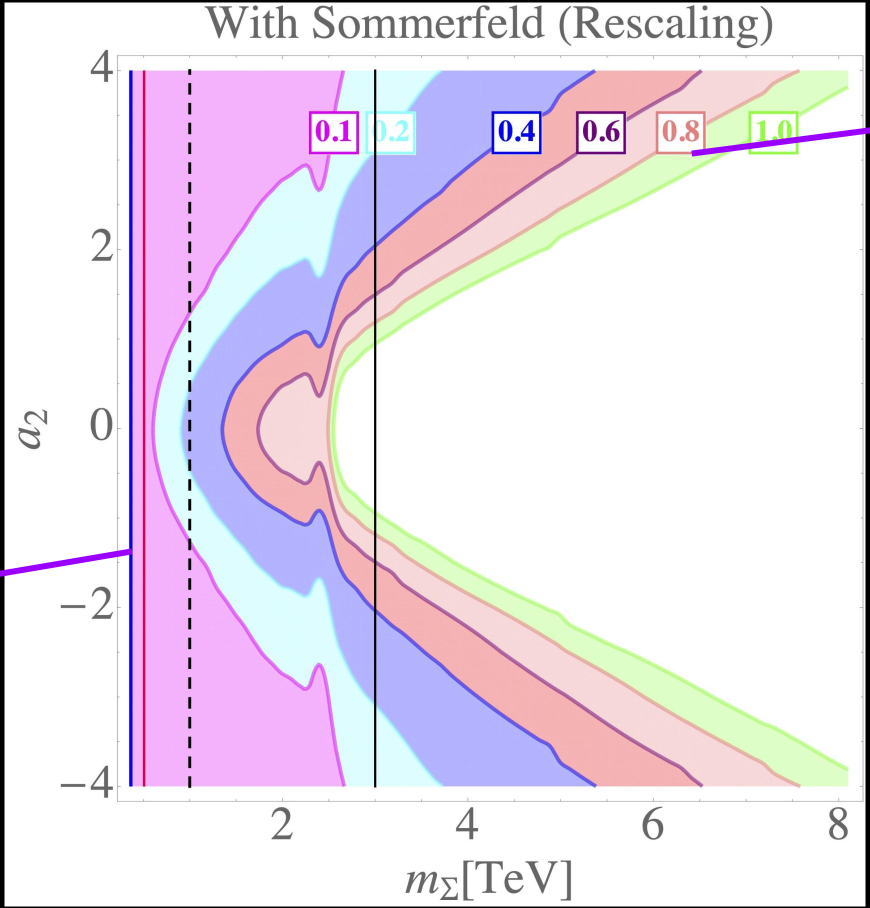
Rescale 13 TeV disappearing track selection requirements - include pile-up scenarios - retain ATLAS tracklet requirements

2003.07867

Benchmark	σ [pb]	ϵ	S	B	$S/\sqrt{B}$
$m_{\Sigma^\pm} = 1.1$ TeV, $\bar{\mu} = 200$	5.8×10^{-2}	3.17×10^{-4}	553	673	21.3
$m_{\Sigma^\pm} = 1.1$ TeV, $\bar{\mu} = 500$	5.8×10^{-2}	3.17×10^{-4}	553	8214	6
$m_{\Sigma^\pm} = 3.1$ TeV, $\bar{\mu} = 200$	9.4×10^{-4}	4.69×10^{-4}	13.3	1.9	9.6
$m_{\Sigma^\pm} = 3.1$ TeV, $\bar{\mu} = 500$	9.4×10^{-4}	4.69×10^{-4}	13.3	27	2.6

Background estimation following results in M. Saito, R. Sawada, K. Terashi, S. Asai, arXiv: 1901.02987

DM Relic Density

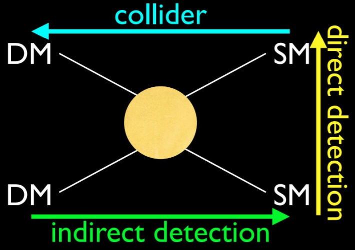


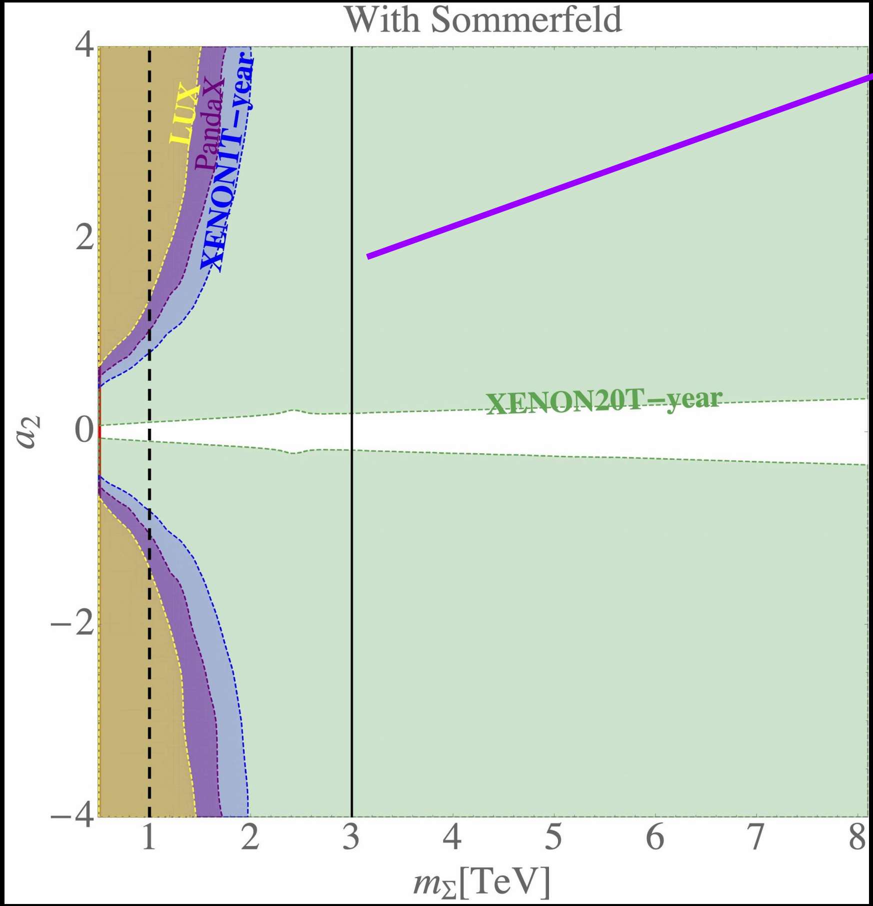
$\Omega_\Sigma / \Omega_{DM}$

LHC Exclusion In red/blue. FCC-hh in black

2003.07867

DM Direct Detection





FCC discovery
Prospects !

Complementarity
between Colliders and
Direct Detection
Experiments !

2003.07867

Take Home messages

New physics may be hiding @ LHC ! We should look EVERYWHERE

Reinterpreting search results to other models requires careful recasting

EW Multiplet DM is in interesting target for the LHC and prospective future colliders

Disappearing charged track searches provide a particularly powerful probe !

Backup

Triplet Scalar DM Model

$$m_h^2 = 2\lambda_0 v^2, \quad m_{\Sigma^0}^2 = m_{\Sigma^\pm}^2 = -\mu_\Sigma^2 + \frac{a_2 v^2}{2} \equiv m_0^2.$$

C.-W. Chiang, G. Cottin, Y. Du, K. Fuyuto, M.J. Ramsey-Musolf [arXiv: 2003.07867]

$$\Delta m = m_{\Sigma^\pm} - m_{\Sigma^0} = \frac{\alpha_2 m_0}{4\pi}\left[f\left(\frac{m_W}{m_0}\right) - c_W^2 f\left(\frac{m_Z}{m_0}\right)\right],$$

M. Cirelli, N. Fornengo and A. Strumia,, Nucl. Phys. B753 (2006) 178–194

DM Processes considered

Annihilation	Coannihilation			
$^*\Sigma^0\Sigma^0 \to W^\pm W^\mp$	$\Sigma^0\Sigma^\pm \to f\bar{f}'$	$^*\Sigma^\pm\Sigma^\mp \to f\bar{f}$	$^*\Sigma^\pm\Sigma^\mp \to h\gamma$	$\Sigma^\pm\Sigma^\mp \to \nu\bar{\nu}$
$^*\Sigma^0\Sigma^0 \to ZZ$	$\Sigma^0\Sigma^\pm \to W^\pm Z$	$^*\Sigma^\pm\Sigma^\mp \to W^\pm W^\mp$	$^*\Sigma^\pm\Sigma^\mp \to hh$	$\Sigma^\pm\Sigma^\pm \to W^\pm W^\pm$
$^*\Sigma^0\Sigma^0 \to hh$	$\Sigma^0\Sigma^\pm \to W^\pm\gamma$	$^*\Sigma^\pm\Sigma^\mp \to ZZ$	$\Sigma^\pm\Sigma^\mp \to Z\gamma$	
$^*\Sigma^0\Sigma^0 \to f\bar{f}$	$^*\Sigma^0\Sigma^\pm \to W^\pm h$	$^*\Sigma^\pm\Sigma^\mp \to Zh$	$\Sigma^\pm\Sigma^\mp \to \gamma\gamma$	

Table 2: Annihilation and coannihilation processes related to the DM relic density calculation, where $f = e, \mu, \tau, u, d, c, s, t, b$ and $\nu = \nu_e, \nu_\mu, \nu_\tau$. Processes starting with an asterisk (*) are a_2 dependent.

C.-W. Chiang, G. Cottin, Y. Du, K. Fuyuto, M.J. Ramsey-Musolf https://arxiv.org/abs/2003.07867

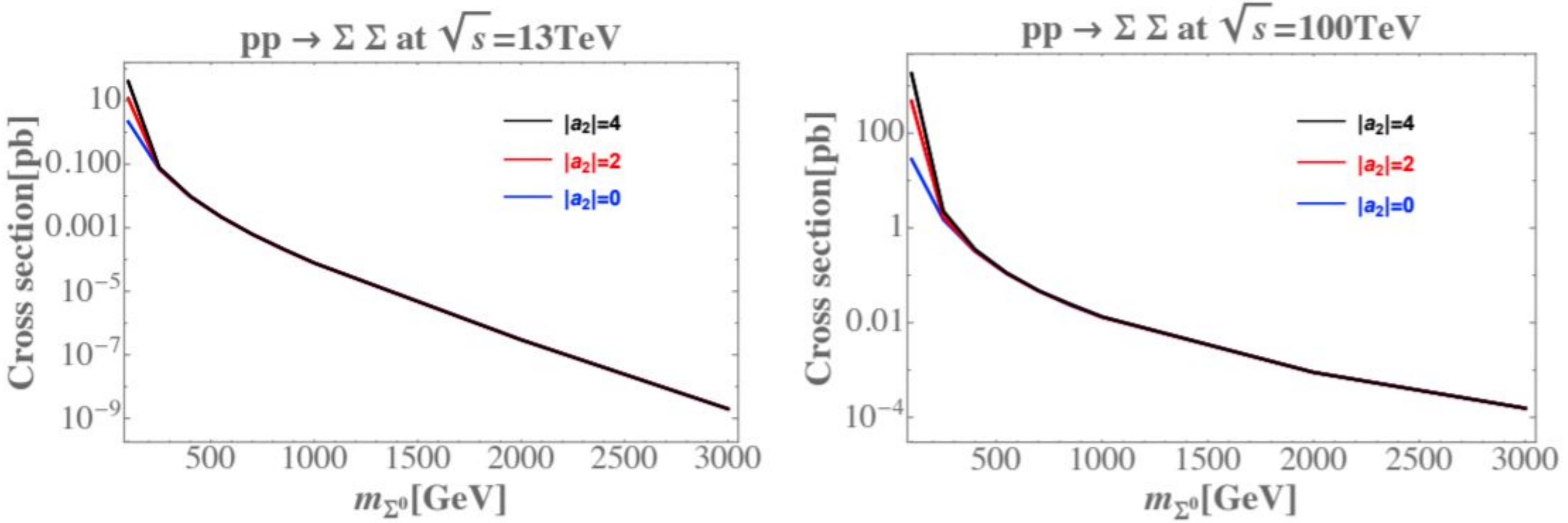


Figure 3: Pair production cross sections of triplet particles $\Sigma = \Sigma^{\pm,0}$ at 13 TeV and 100 TeV pp colliders as a function of m_{Σ^0} with representative values of a_2.