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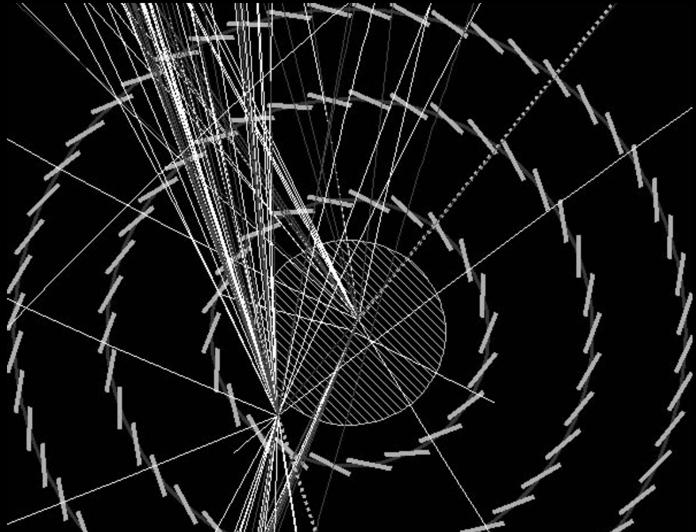
The lifetime frontier @ LHC: Simplified Models and Reinterpretation of Long-Lived Particle Searches

Giovanna Cottin

Based on work with the LLP Community

(Editors: J. Beacham, G. Cottin, D. Curtin, N. Desai, J. Evans,
S. Kraml, A. Lessa, Z. Liu, M. Ramsey-Musolf, J. Shelton, B. Shuve)

NCTS Annual Theory Meeting
December 2018



Outline

We = the LLP Community

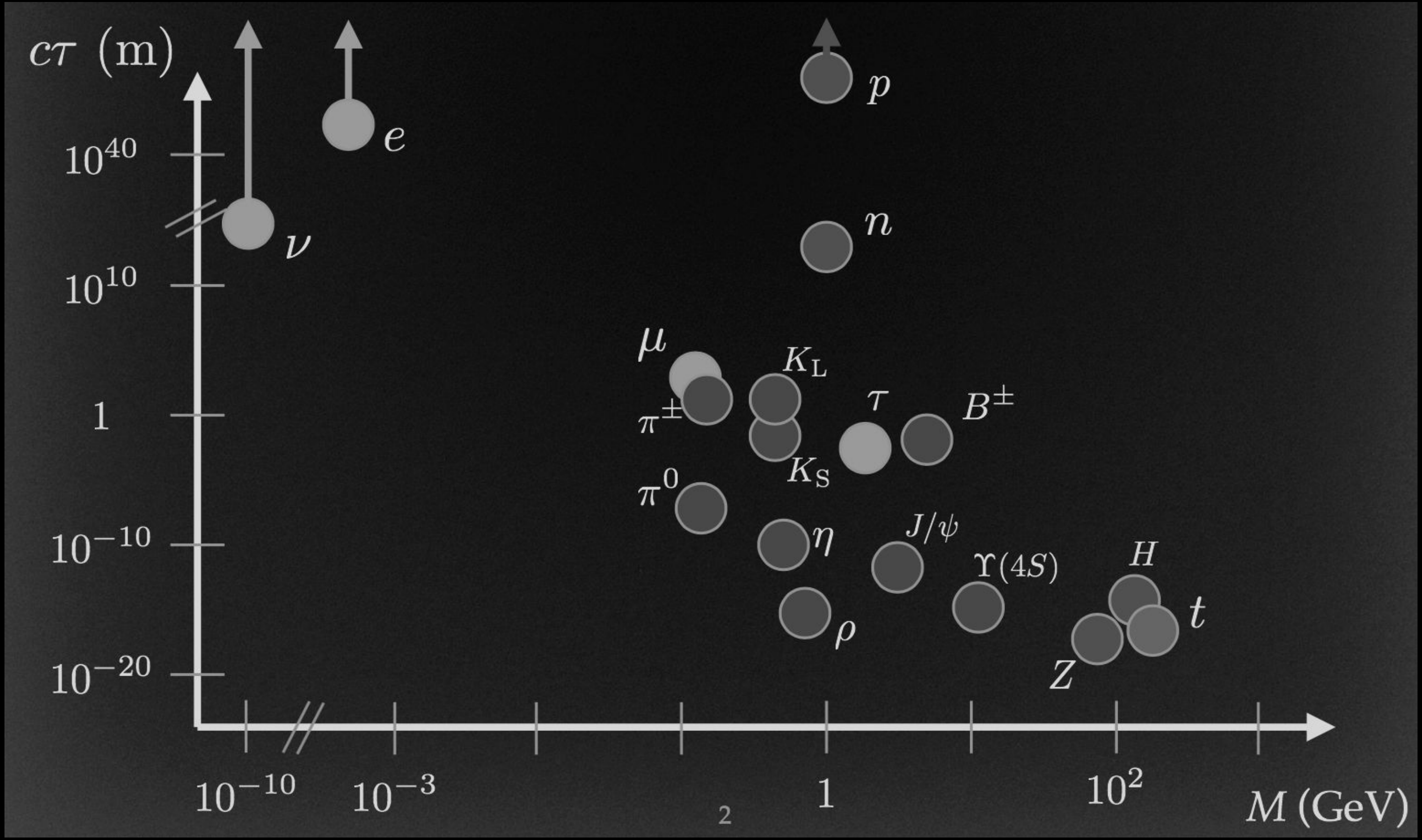
Motivation: Importance of long-lived particles (LLPs) in BSM theories

LLPs at the LHC. Searches for non-standard signatures that are difficult to reinterpret to other physics models. Information from the experiments in appropriate format is essential

We have identified reinterpretation challenges and ways to address them

We have a strategy ahead in the development of Simplified Models to systemize these searches and also facilitate reinterpretation

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
Dark Matter
Baryogenesis
Neutrino Masses
Naturalness

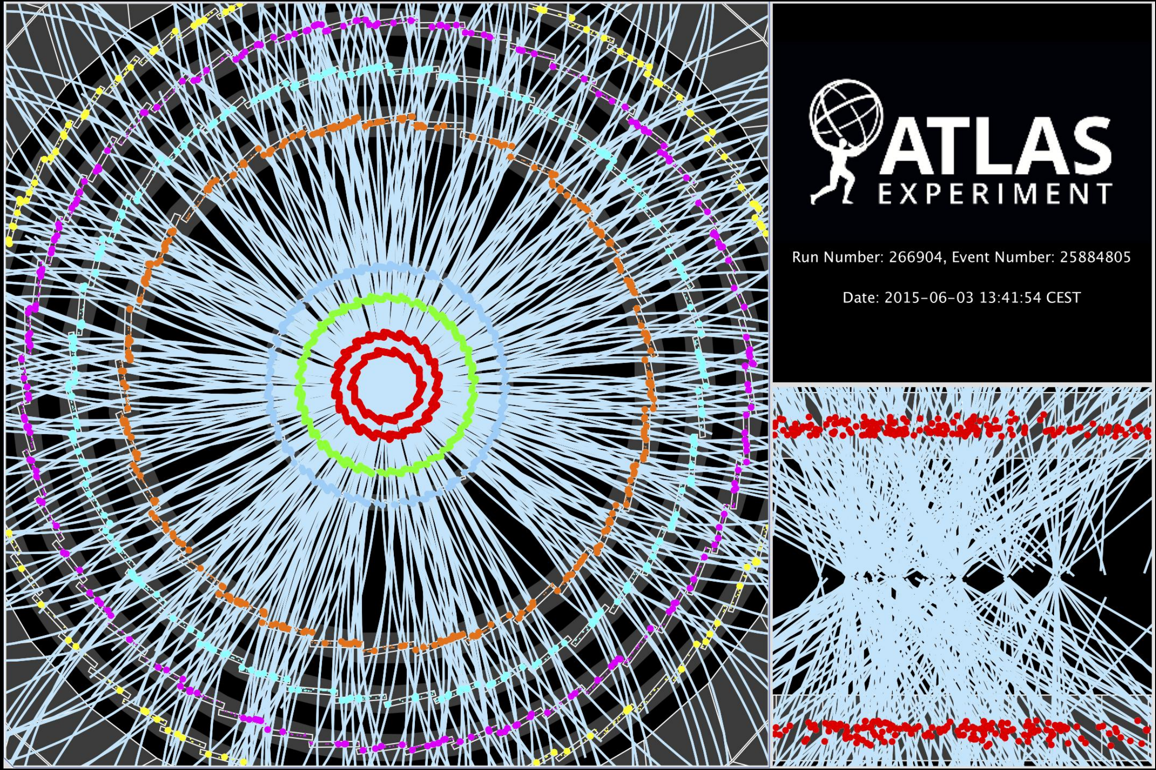
Theory
SUSY RPV, mini-split
Higgs Portal Hidden Valley/Neutral Naturalness
Gauge Portal Z', dark photon
Dark Matter EWK Multiplets, SIMPs
RH Neutrinos nuMSM, Left-Right Symmetry

Phenomenology
LLPs/ signatures

Experiment
Data

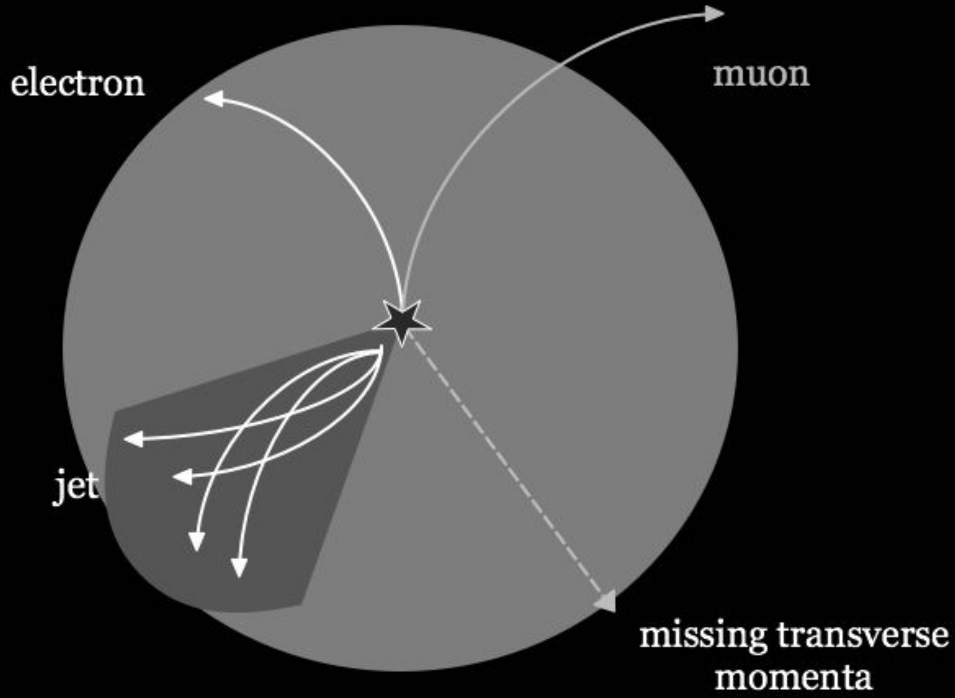
See also MATHUSLA physics case for nice review on models and motivations in arXiv:1806.07396

… and we are not seeing it at the LHC Run 2 finalised this month !



Source: CERN https://cds.cern.ch/record/2022202

… and we are not seeing it at the LHC
Run 2 finalised this month !



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

Searches can target specific lifetimes using different parts of the detector

Detection usually requires special triggers and reconstruction

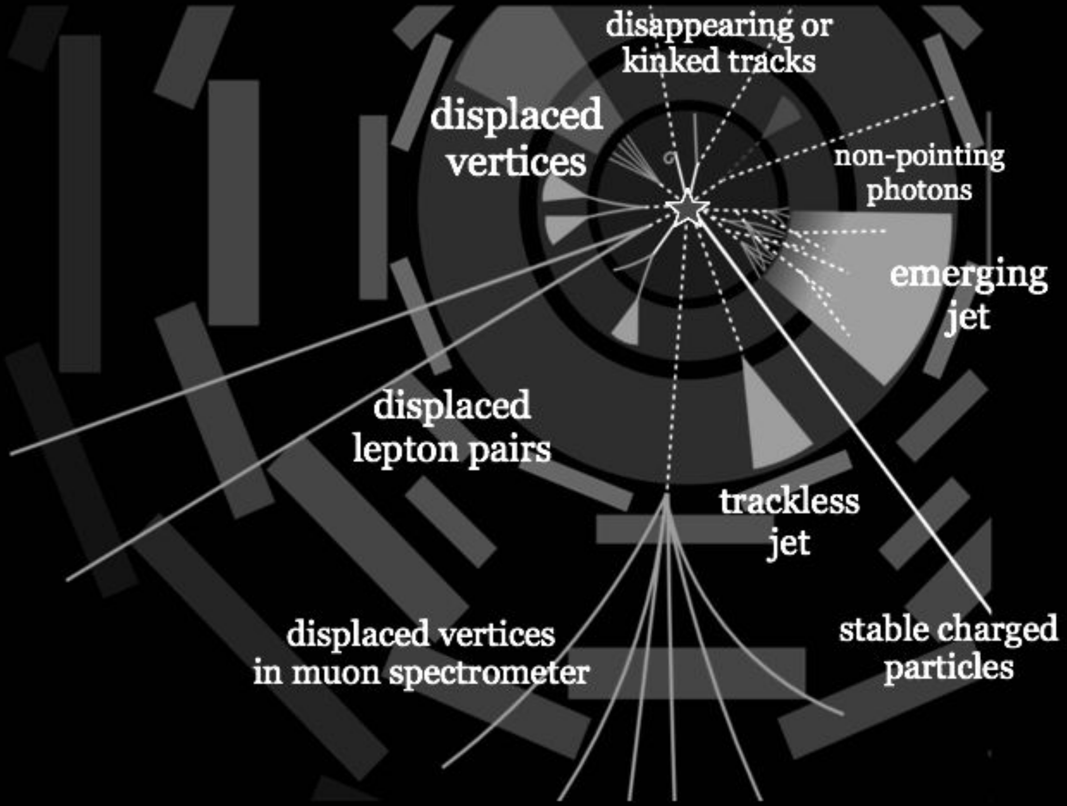


Image Redone Inspired by Heather Russell

Very **CHALLENGING SEARCHES !!!**

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?

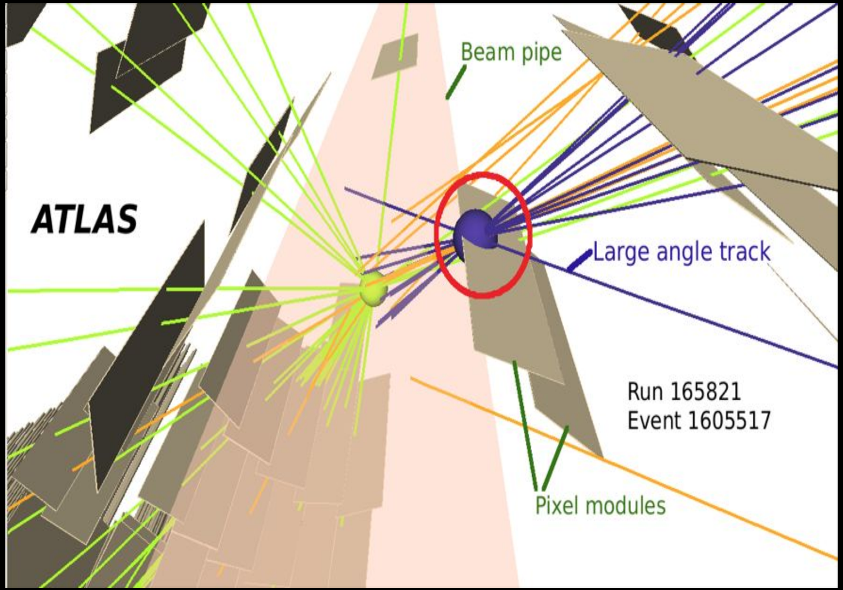
We need extensive information about analysis details !

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

LLPs Reinterpretation Challenges

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: ATLAS Multitrack Displaced Vertex Search [arXiv:1710.04901]



Source: ATLAS Event Display arXiv:1109.2242

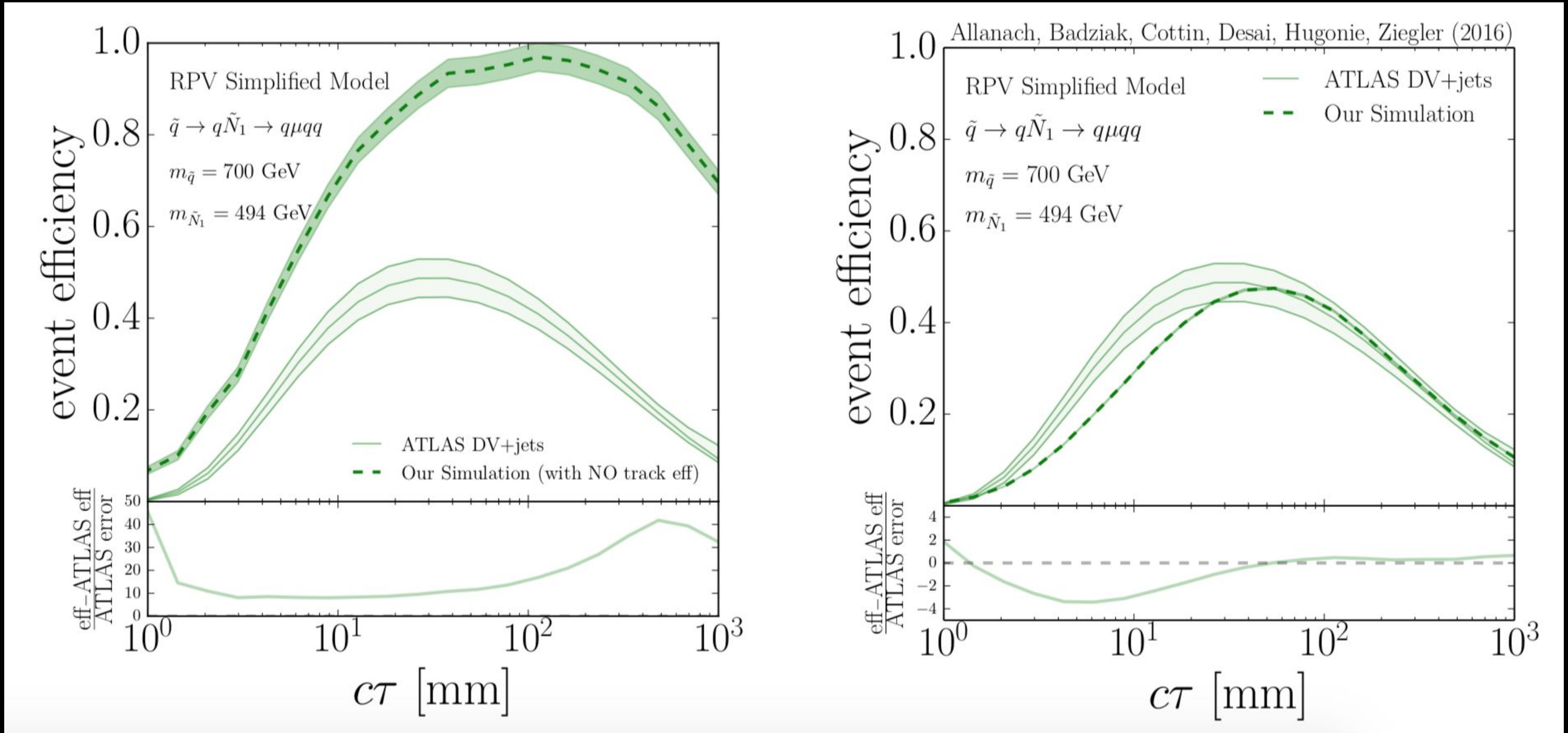
Looks for high-mass and track multiplicity DVs in inner tracker mDV>10 GeV, nTrk>5

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

Veto vertices in material layers (dominant background vertices) with a 3D material. After this, ZERO background search

Example: Recasting ATLAS Displaced Vertex Search [arXiv:1504.05162]

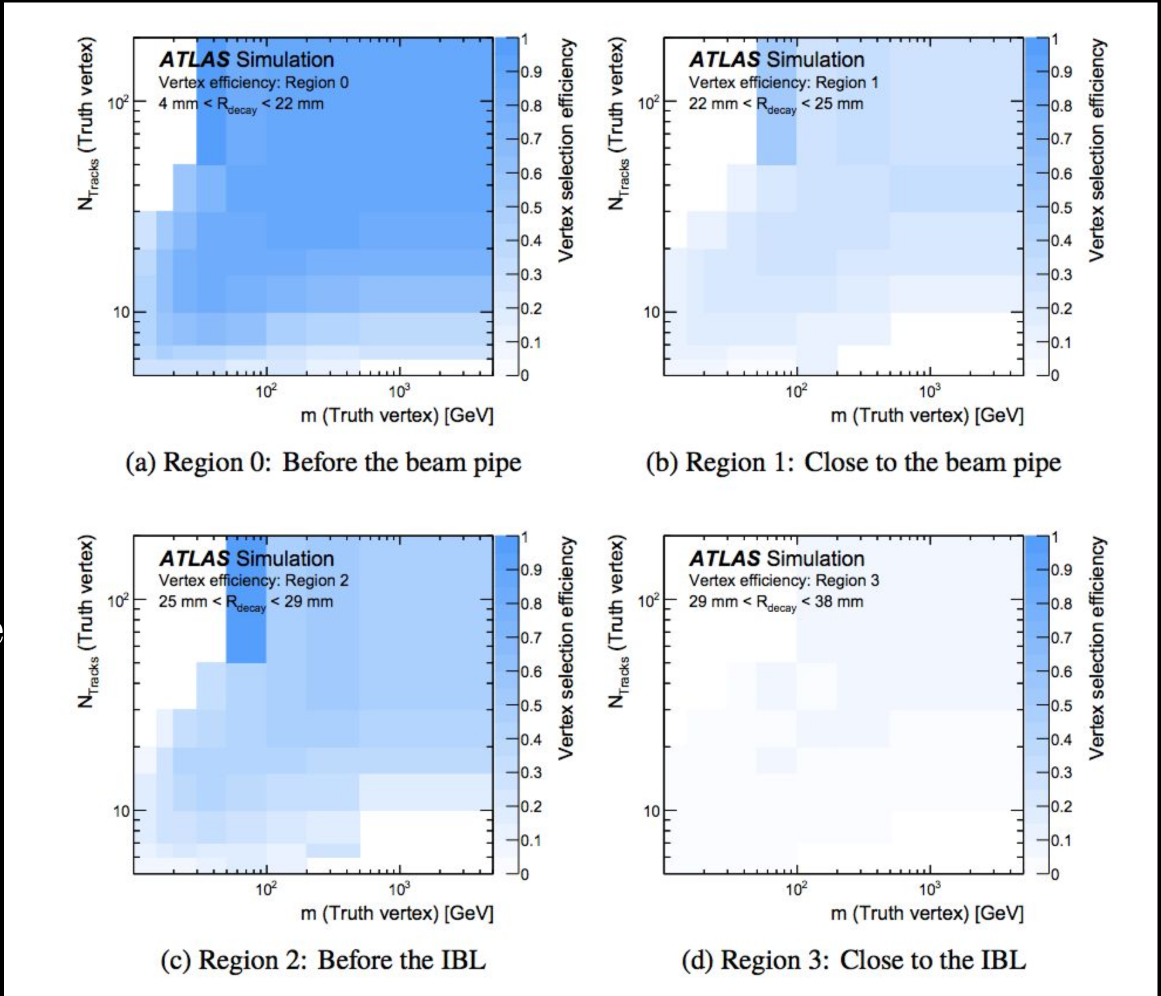
8 TeV Validation : Not much recasting info. Ad hoc track efficiency function defined in [arXiv:1606.03099] B. C. Allanach, M. Badziak, G. Cottin, N. Desai, C. Hugonie and R. Ziegler



Example: Recasting ATLAS Displaced Vertex Search (arXiv:1710.04901)

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

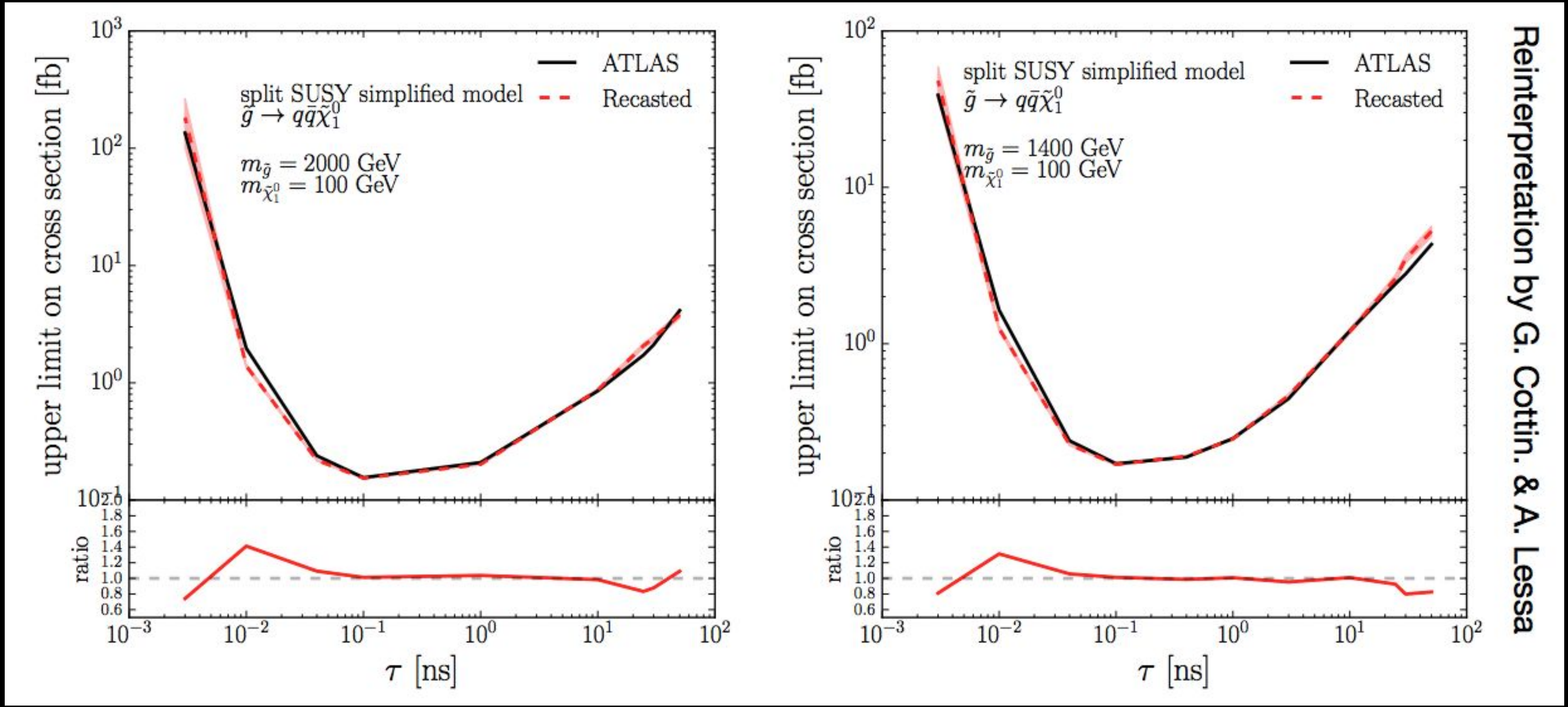
Can be applied to truth-level MC (nTrk, mDV, rDV)



Example: Recasting ATLAS Displaced Vertex Search (arXiv:1710.04901)

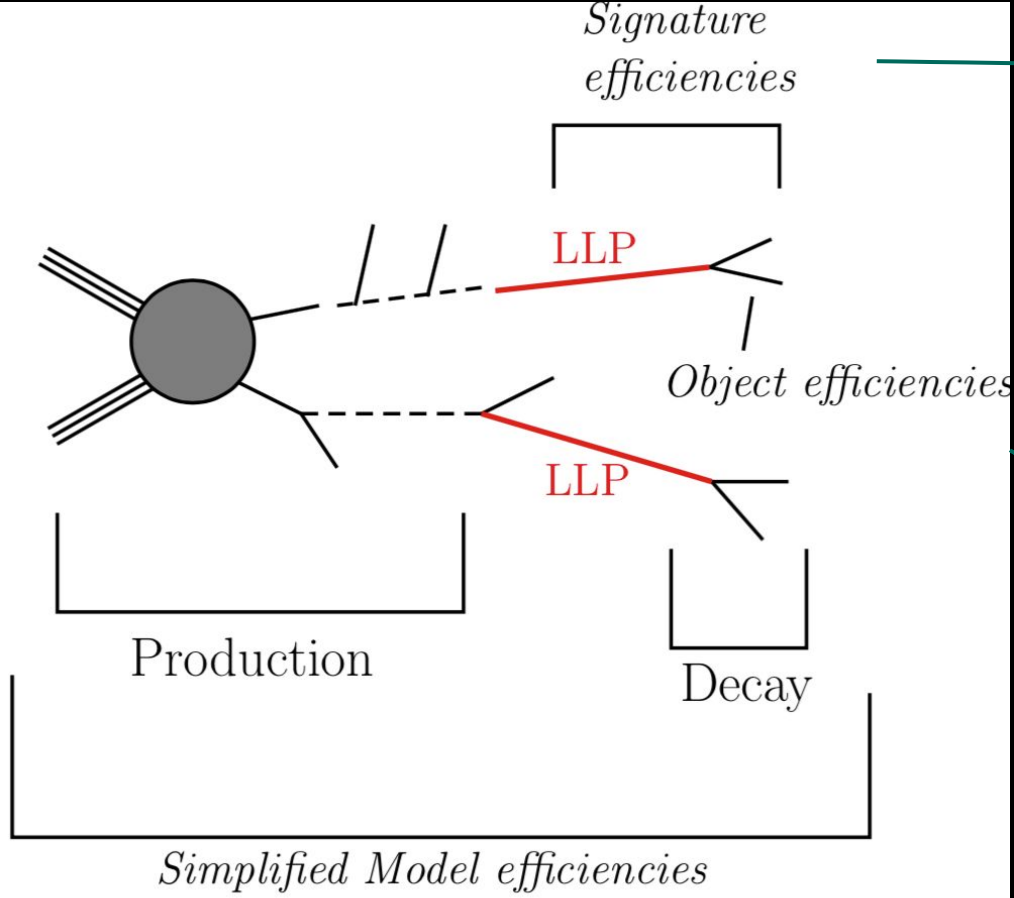
13 TeV Validation : Limits Looking MUCH alike for Les Houches 2018 !!!

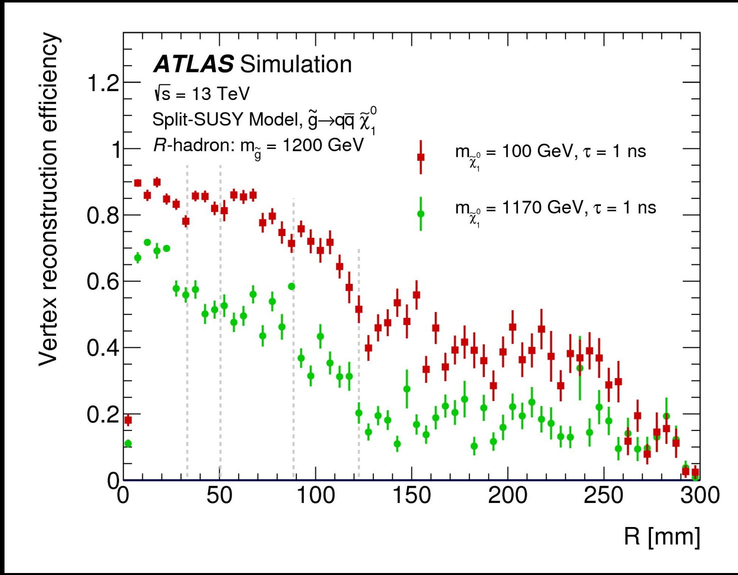
[1803.10379] Contribution 22 , G. Cottin, N. Desai, J. Heisig and A. Lessa



Source: arXiv:1710.04901

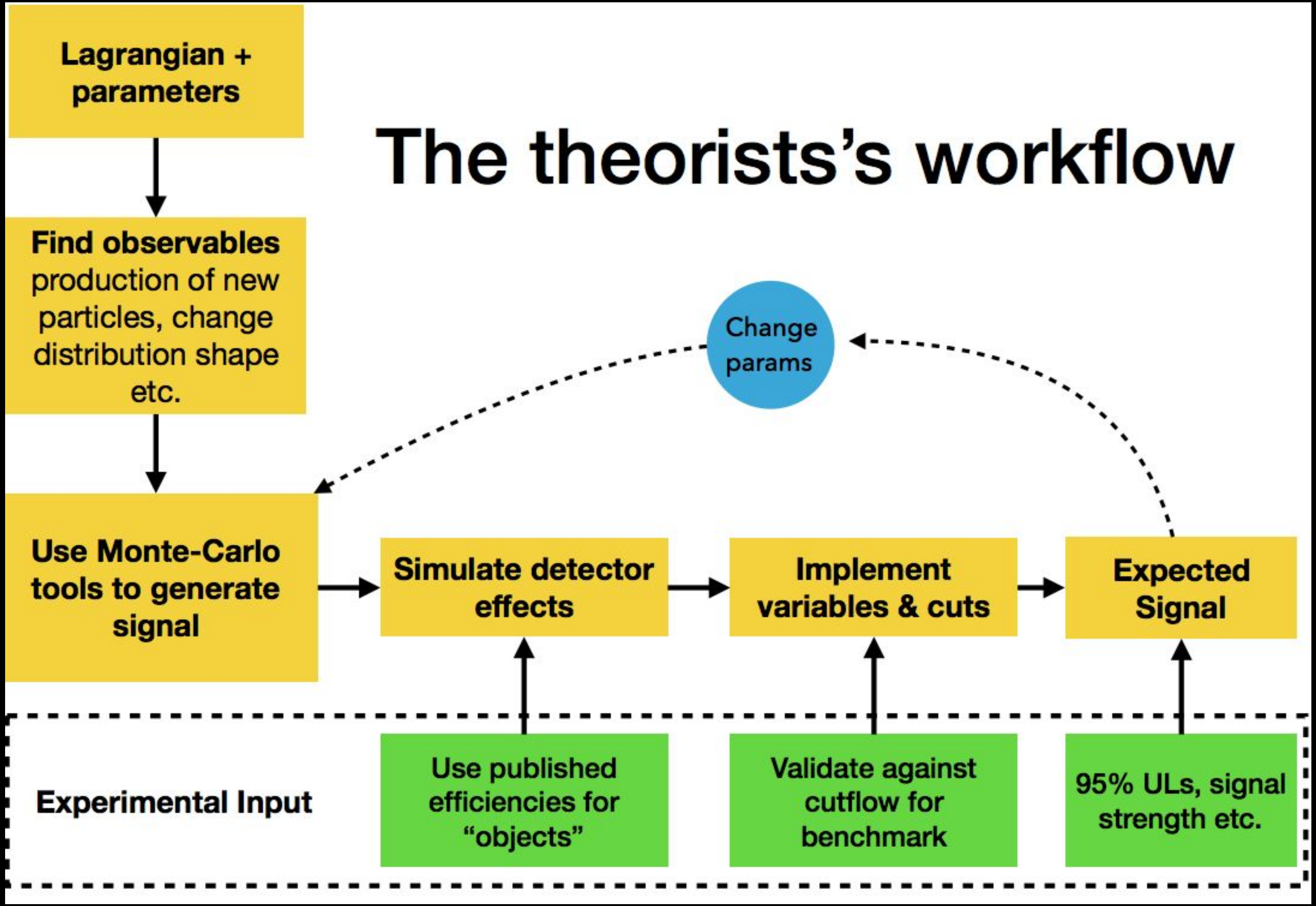
Levels of Information





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

Slide from Nishita Desai @ LLP Workshop, CERN

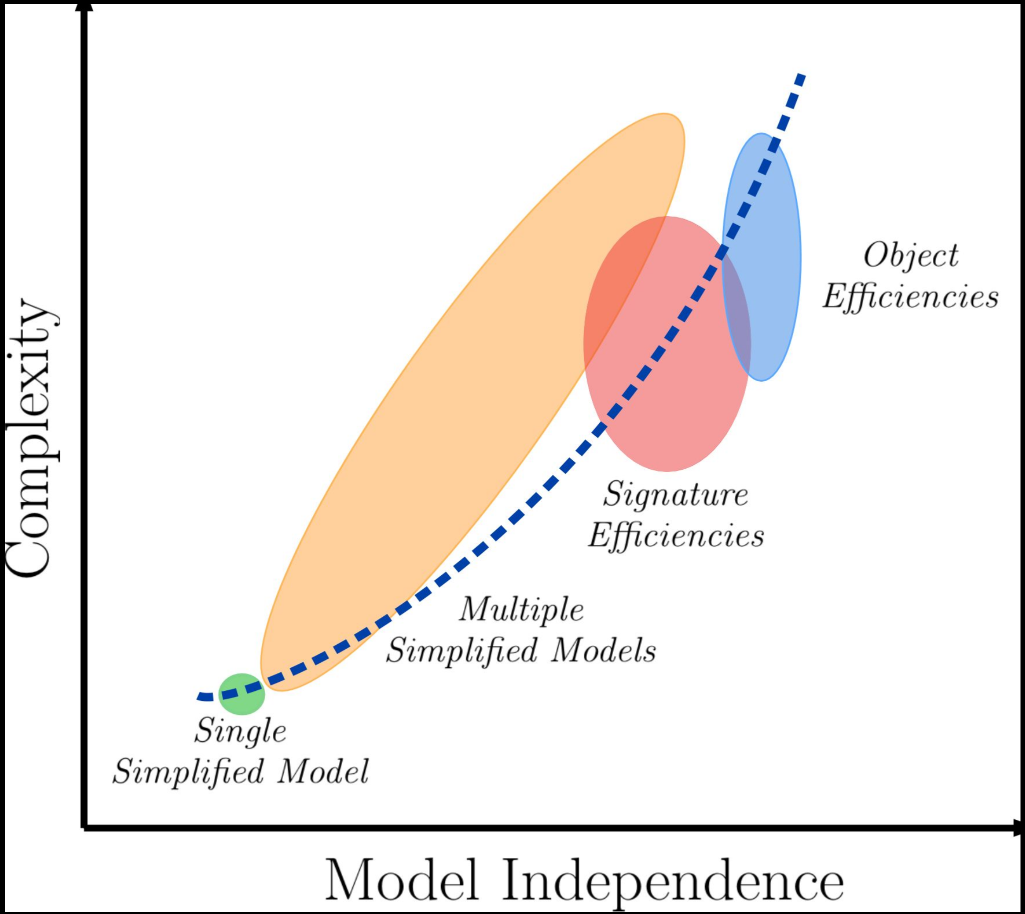


Simplified models needed to define and benchmark LLP searches. They can also help with reinterpretation !

Simplified models motivated by complete models.

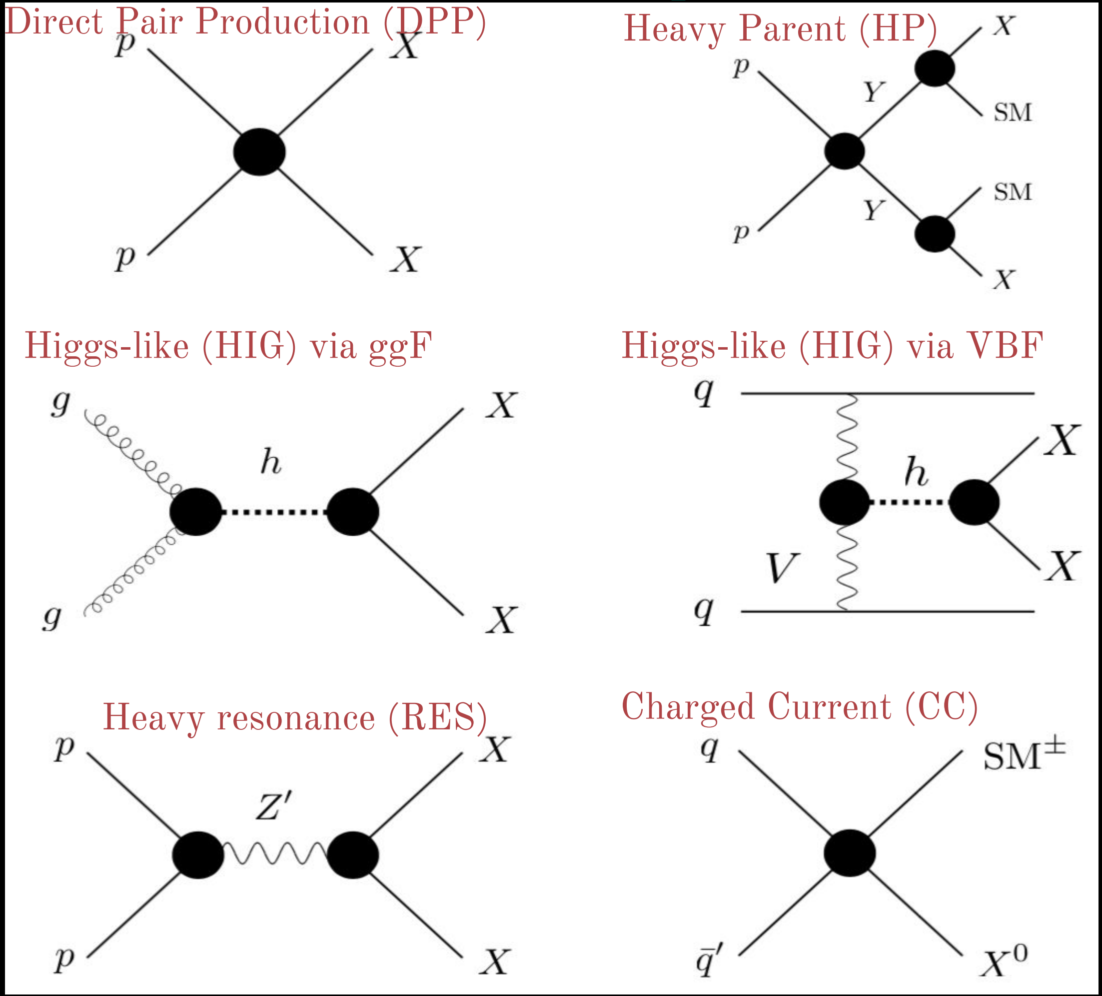
They have assumptions on LLP production, decay and quantum numbers.

Few parameters (i.e masses and LLP lifetime)



Source: LLP White Paper, to appear

Simplified Models for LLPs @ LHC : A Proposal



Source: LLP White Paper, to appear

Example: Neutral LLP Channels

Source: LLP White Paper, to appear

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*

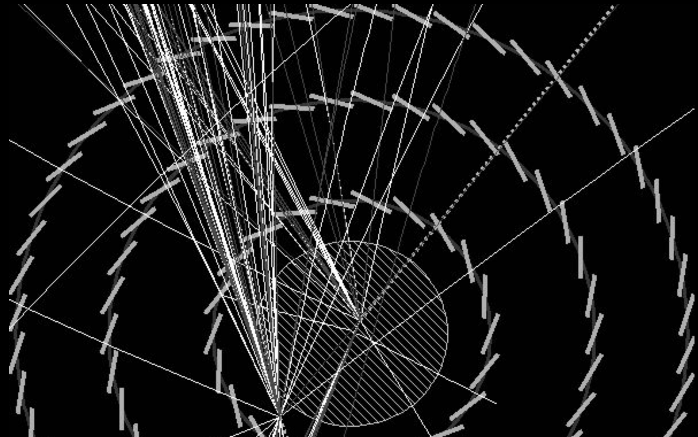
Filled entries happen in benchmark theories:
SUSY-like, Higgs portal, Gauge portal, RH Neutrinos, DM

LLPs are very well motivated ! Need to design a systematic search program

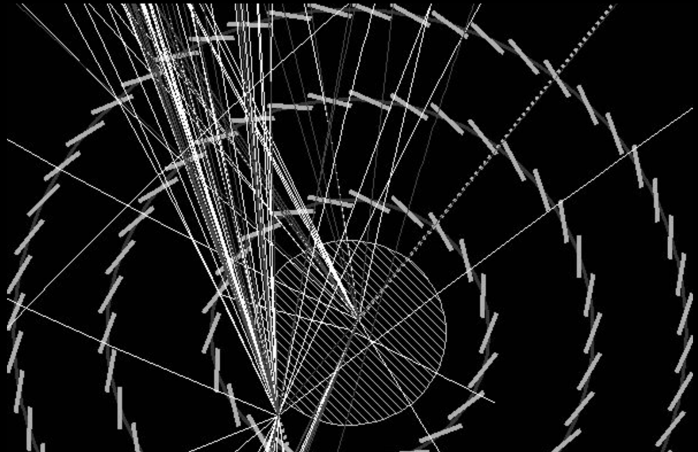
Recommendations to our experimental friends (Much more soon in our White Paper !)

- Provide LLP reconstruction and selection efficiencies at the signature or object level
- Present results for at least two distinct benchmark models, with distinct event topologies
- Present cut-flow tables
- Clearly specify if information from old analysis can be used in superseded version
- When object or signature-level efficiency maps are not feasible, provide efficiencies for a diverse array of **Simplified Models** (our proposal) as function of relevant parameters (LLP mass and lifetime)

One day, we hope to move from constraints to discovery. Are we ready for when that time comes?
(B. Shuve)



Backup



Simplified Models Advantages

- Parametrization in terms of few physical parameters
- Unified format applicable to a wide range of searches

Simplified Models Disadvantages

- Results can not be applied to other LLP and production modes, yielding conservative limits if the LLP signal is composed from multiple topologies

Full Example on Recasting Displaced Searches @ LHC. Looking for a light, long-lived sterile neutrino

Based on

Phys. Rev. D 97, 055025 (2018) [arXiv:1801.02734]

G. Cottin, J.C. Helo, M. Hirsch

Left-Right Symmetric Models

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)

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

Neutrino masses explained by the so-called see-saw mechanism, introducing the existence of massive, right-handed (sterile) neutrinos.

Sterile neutrinos with Majorana masses covering various mass ranges.

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

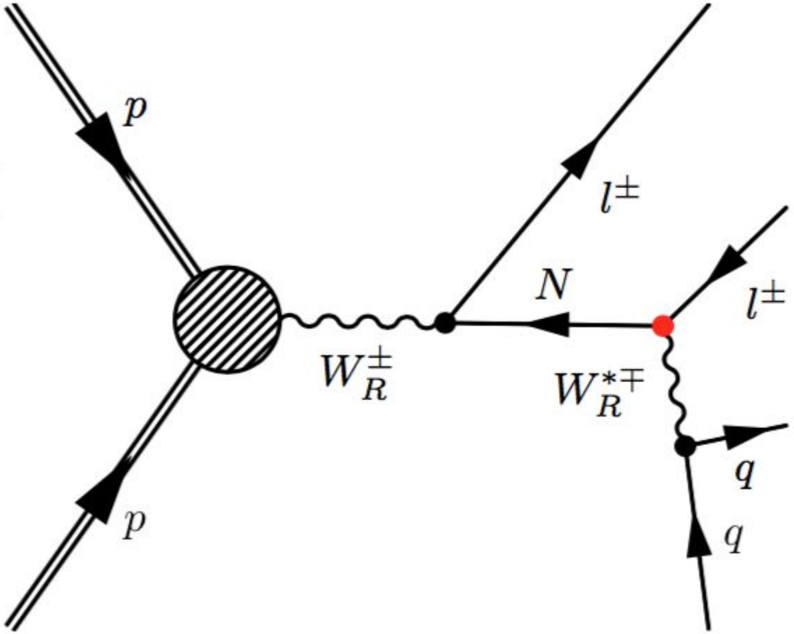
Source: nobelprize.org

Displaced vertex Searches @ LHC. Looking for a light, long-lived sterile neutrino from Left-Right symmetric model

Phys. Rev. D 97, 055025 (2018) [arXiv:1801.02734] G. Cottin, J.C. Helo, M. Hirsch

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

$$m_N \ll m_{W_R}, m_N < m_W$$



LR model:

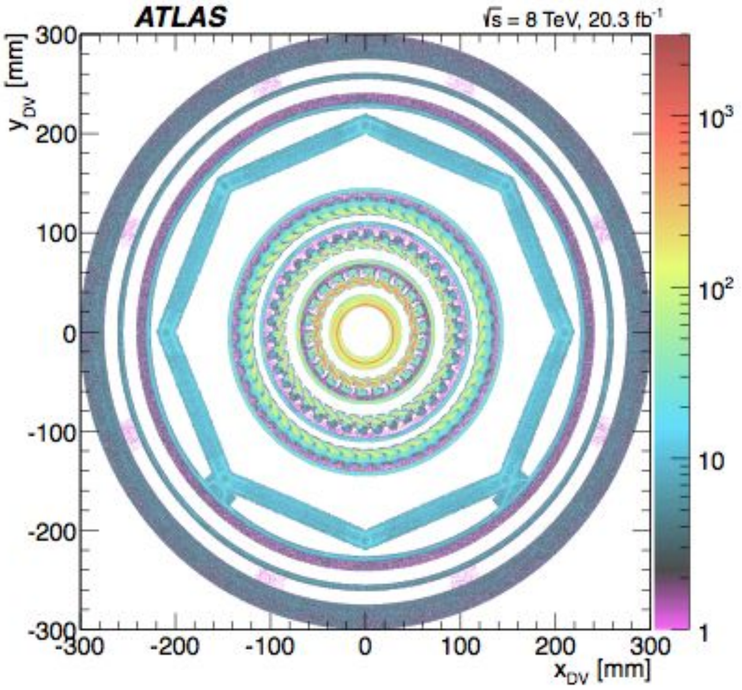
J. C. Pati and A. Salam, Phys. Rev. D10, 275 (1974)
R. N. Mohapatra and J. C. Pati, Phys. Rev. D11, 2558 (1975)
R. N. Mohapatra and G. Senjanovic, Phys. Rev. D23, 165 (1981)

ATLAS DV analysis strategy

* Look for high-mass, high-track multiplicity displaced vertices in inner tracker with mass>10 GeV and at least 5 tracks

* Standard ATLAS tracking algorithms are re-run with looser cuts to gain efficiency for high-d0 tracks

* Veto vertices in material layers (dominant background vertices) with a 3D material. After this, almost zero background search



Source: PRD92 (2015) 7, 072004

Event Simulation and Selections

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

We generate events in MadGraph and interphace with Pythia 8.
Detector response to physics objects modeled inside Pythia.

Original analysis triggers on missing transverse momenta.
We propose to trigger on the prompt lepton. We require:

- electron with pT>25 GeV
- One “trackless jet” (a jet with sum_pT of tracks less than 5 GeV) with pT>70 GeV or two trackless jet with pT>25 GeV

At least one DV with:

- Distance between interaction point and decay position > 4 mm
- Decays within rDV and |zDV|<300 mm
- At least 5 charged decay products with pT>1 GeV and |d0|>2mm
- Invariant mass of DV > 10 GeV, under charged pion mass hypothesis for tracks

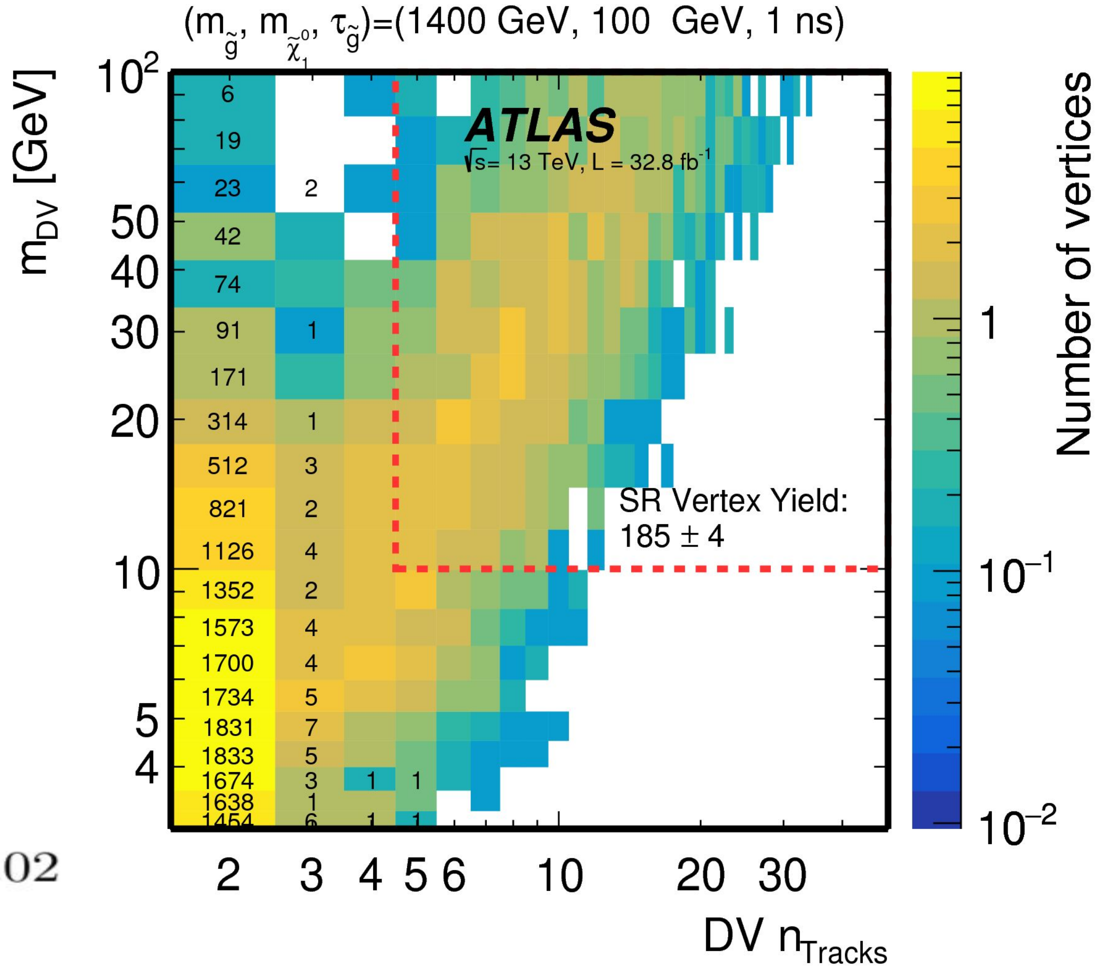
We find LOW sensitivity to the LR model

$\sqrt{s} = 13$ TeV

$m_N = 20$ GeV, $m_{W_R} = 4$ TeV and $c\tau_N = 1.3$ mm

	N	Rel. ϵ [%]	Ov. ϵ [%]
All events	10000	100	100
Prompt electron	8721	87.2	87.2
Trackless jet	8704	99.8	87.0
DV fiducial	7615	87.5	76.1
DV N_{trk}	528	6.9	5.3
DV m_{DV}	89	16.9	0.9
DV efficiency	6	6.7	0.06

ATLAS yields

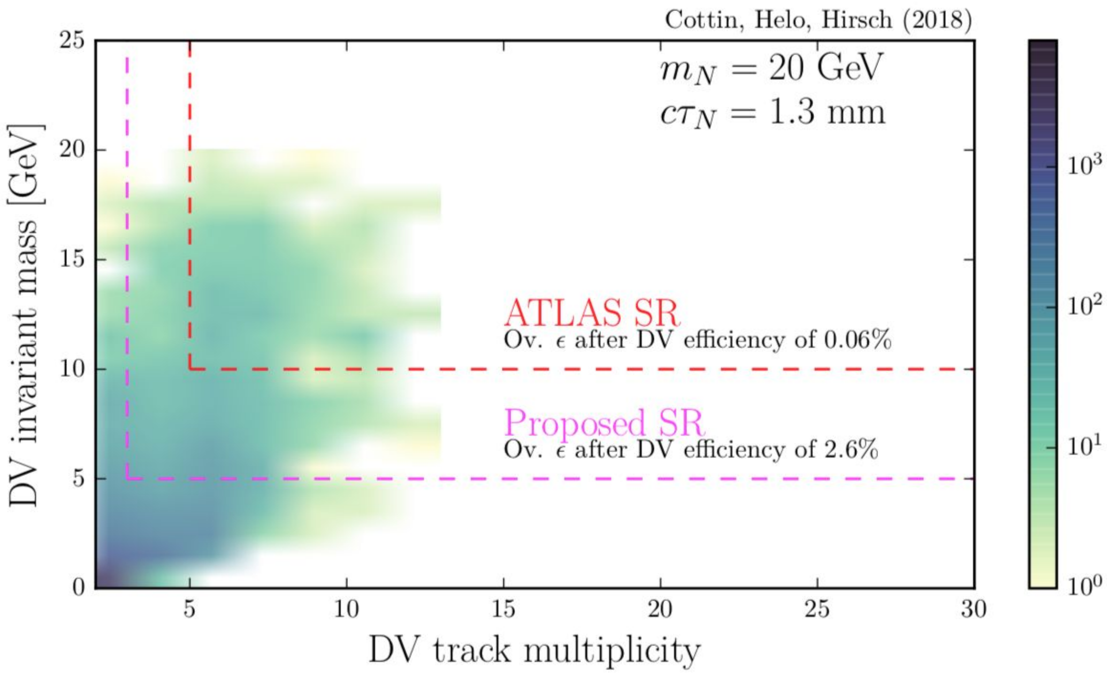


$$N_{\mathrm{DV}}^{\mathrm{BG}} = 0.02 \pm 0.02$$

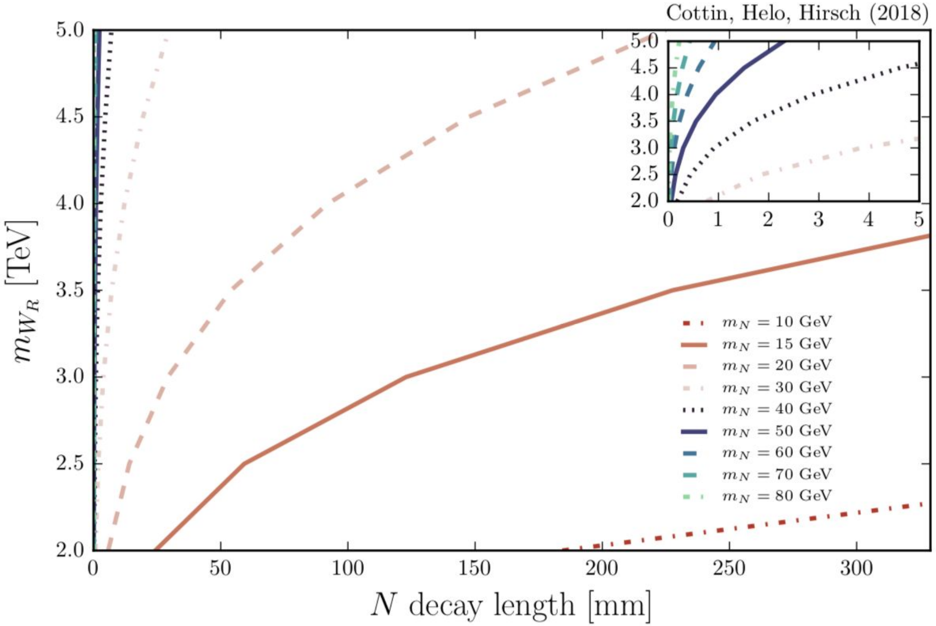
Source: https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/SUSY-2016-08/

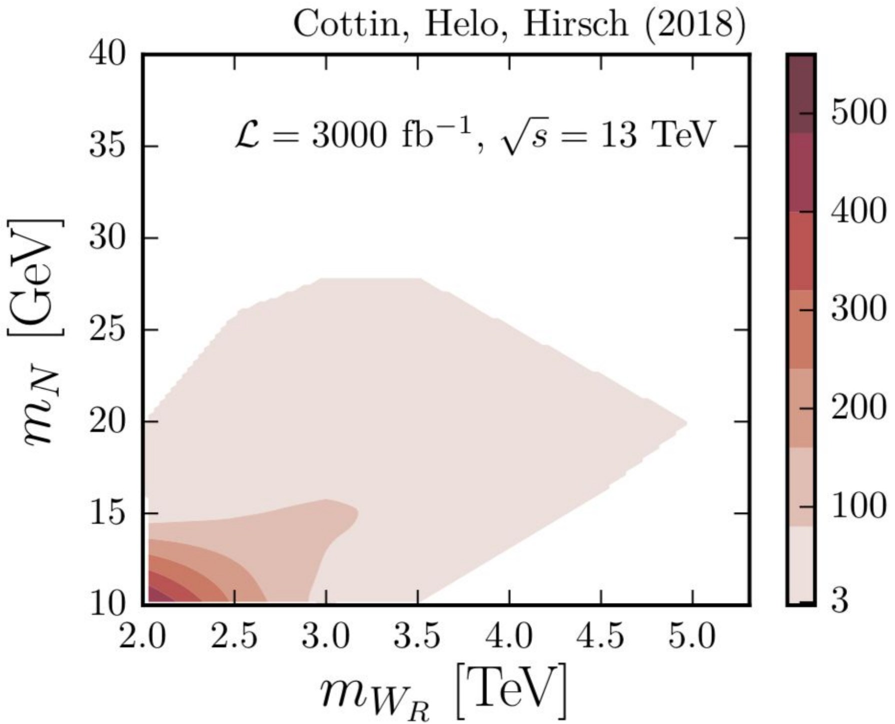
ATLAS Multitrack DV 13 TeV search [arXiv:1710.04901]

- Signatures inside inner tracker
- Analysis triggers on MET. We use prompt lepton. High mass and track multiplicity DVs. We relax these cuts
- Analysis provides efficiency maps depending on DV mass, tracks and decay distance (within 4 and 300 mm). We use them to model detector response to DVs (and assume model independance of factorized maps at the vertex level)



Sensitivity with “prompt lepton + loose DV multitrack”





Acceptance region:

$$10 \text{ GeV} < m_N < 40 \text{ GeV}$$

$$2 \text{ TeV} < m_{W_R} < 5 \text{ TeV}$$

Optimized cuts in ATLAS DV multitrack inspired search needed to cover more parameter space in LR model

Simplified Models for LLPs

Based on

LLP White Paper, to appear

Example: Neutral LLP Channels

Source: LLP White Paper, to appear

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*

Table 2.1: **Simplified model channels for neutral LLPs.** The LLP is indicated by X. Each row shows a separate production mode and each column shows a separate possible decay mode, and therefore every cell in the table corresponds to a different simplified model channel of (production)×(decay). We have cross-referenced the UV models from Section 2.2 with cells in the table to show how the most common signatures of complete models populate the simplified model space. The asterisk (*) shows that the model definitively predicts missing energy in the LLP decay. A dagger (†) indicates that this particle production × decay scenario is not present in the *simplest and most minimal* implementations of the umbrella model, but could be present in extensions of the minimal models. When two production modes are provided (with an "or"), either simplified model can be used to cover the same experimental signatures.

Example: Charged LLP Channels

Source: LLP White Paper, to appear

Production \ Decay	$\ell + \text{inv.}$	$jj(+\text{inv.})$	$jj\ell$	$\ell\gamma$
DPP: chargino pair or slepton pair	SUSY DM*	SUSY DM*	SUSY	†
HP: $\tilde{q} \to jX$	SUSY DM*	SUSY DM*	SUSY	†
RES: $Z' \to XX$	Z′, DM*	Z′, DM*	Z′	†
CC: $W' \to X + \text{inv.}$	DM*	DM*	RHν	†

Table 2.2: **Simplified model channels for electrically charged LLPs, $|Q| = 1$.** The LLP is indicated by X. Each row shows a separate production mode and each column shows a separate possible decay mode, and therefore every cell in the table corresponds to a different simplified model channel of (production)$\times$(decay). We have cross-referenced the "well-motivated" UV models from Section 2.2 with cells in the table to show how the most common signatures complete models can be linked to the simplified model space. The asterisk (*) shows that the model definitively predicts missing energy in the LLP decay. A dagger (†) indicates that this particle production $\times$ decay scenario is not present in the *simplest and most minimal* implementations of the umbrella model, but could be present in extensions of the minimal models. When two production modes are provided (with an "or"), both production simplified models can be used to cover the same experimental signatures.

Example: Coloured LLP Channels

Source: LLP White Paper, to appear

Production \ Decay	$j+\text{inv.}$	$jj(+\text{inv.})$	$j\ell$	$j\gamma$
DPP: squark pair or gluino pair	SUSY	SUSY	SUSY	†

Table 2.3: **Simplified model channels for LLPs with color charge.** The LLP is indicated by X. Each row shows a separate production mode and each column shows a separate possible decay mode, and therefore every cell in the table corresponds to a different simplified model channel of (production)×(decay). We have cross-referenced the "well-motivated" UV models from Section 2.2 with cells in the table to show how the most common signatures complete models can be linked to the simplified models.A dagger (†) indicates that this particle production × decay scenario is not present in the *simplest and most minimal* implementations of the umbrella model, but could be present in extensions of the minimal models. When two production modes are provided (with an "or"), both production simplified models can be used to cover the same experimental signatures.