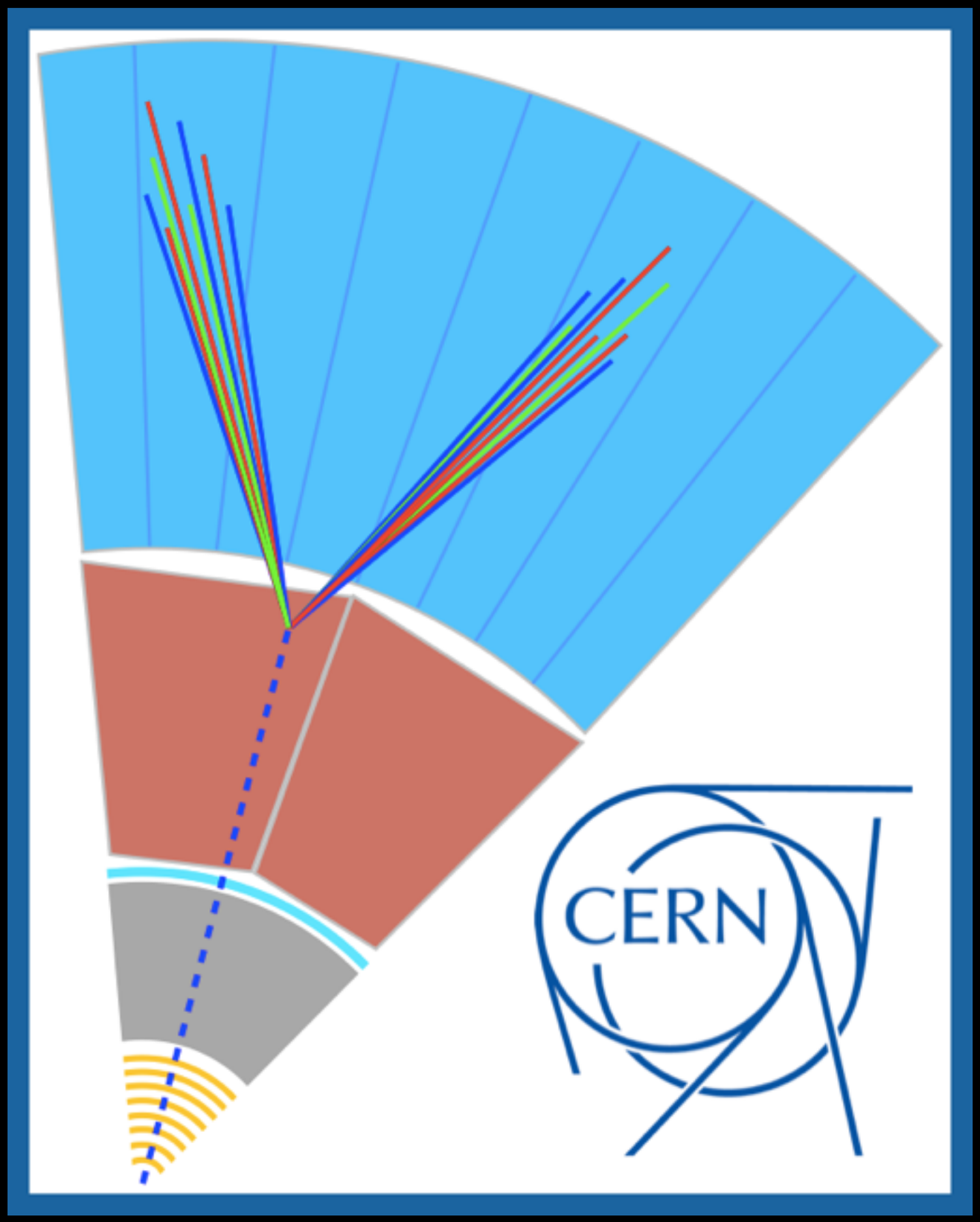


LHC Long-Lived Particle Community

Some thoughts about dark matter

DMWG Meeting

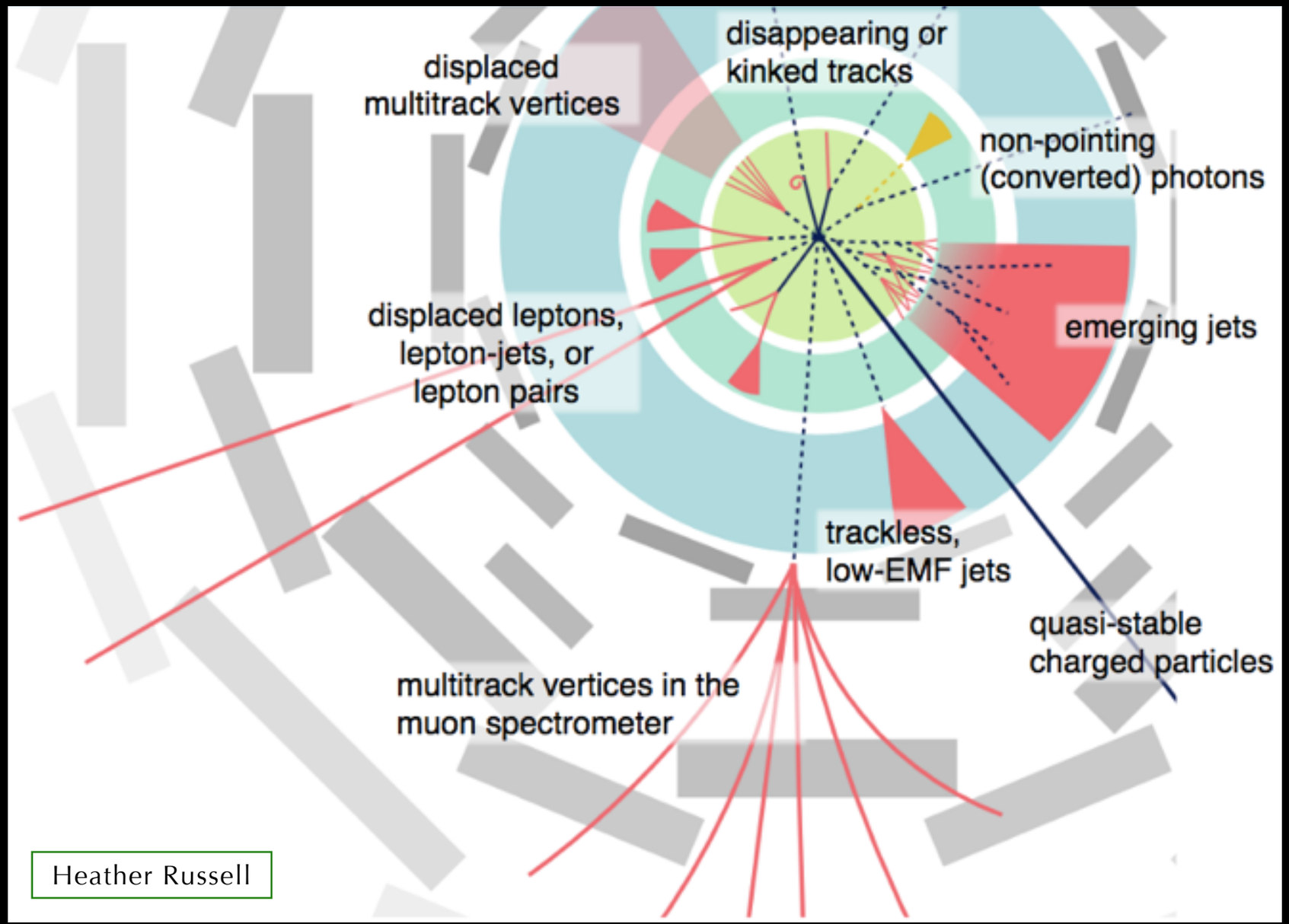
18 December 2017

James Beacham
[ATLAS/Ohio State]
Brian Shuve
[Harvey Mudd]

on behalf of the group

The LHC LLP Community

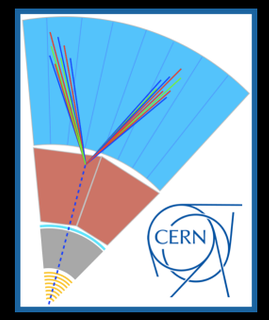
We map LLP signature space



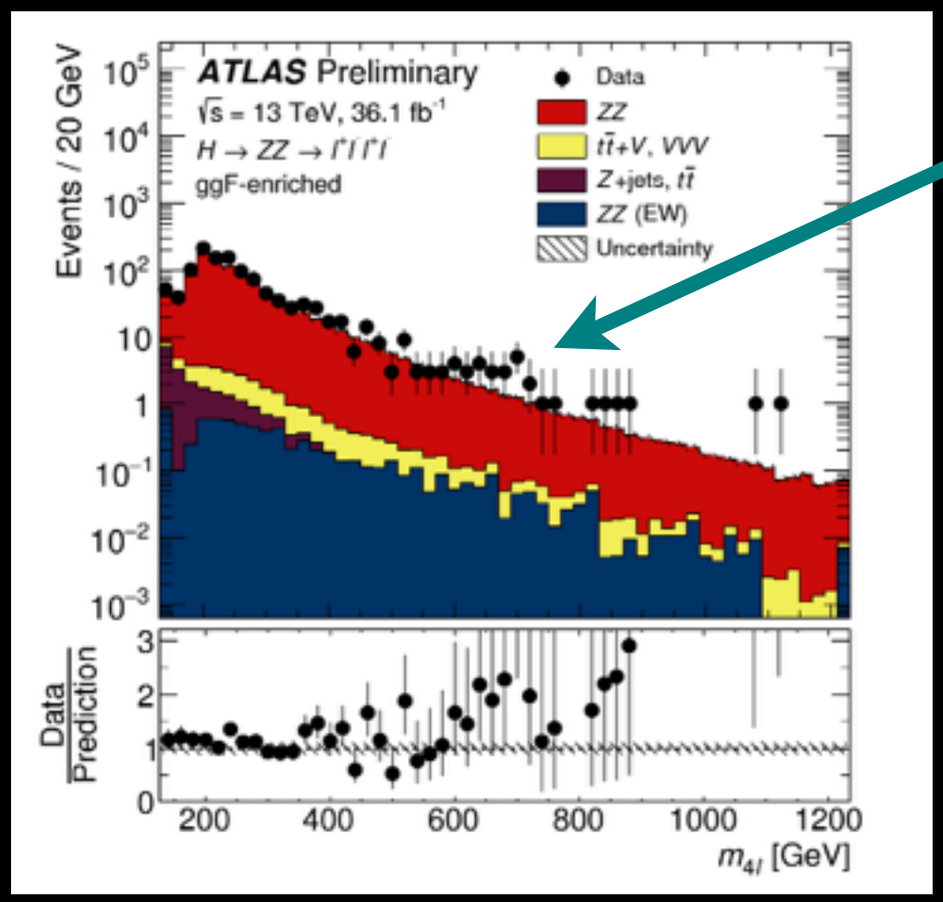
What exactly do we mean by long-lived particle in the LHC context?

For our purposes, LLP = BSM particle that dies (gives up all its energy or decays to SM) somewhere in the detector acceptance of LHCb, CMS, ATLAS, MilliQan, Moedal, FASER, CODEXb, MATHUSLA, etc.

Why a signature-based community?



Our first extensive look at 13 TeV at the LHC yields impressive agreement with Standard Model expectations and no huge, immediate resonances or excesses



?

There are no more guarantees and no ace-in-the-hole motivations (WIMP miracle in tension, lack of plain vanilla MSSM, etc.)

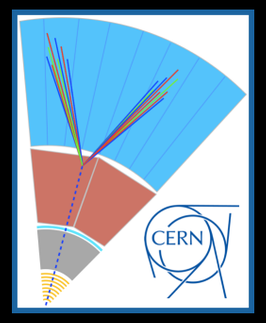
We must shift from theory-driven search strategies to signature-driven ones

We're eager to see what 120/fb at the LHC and 3/ab at the HL-LHC uncover

But our job is to map out parameter and signature space, with a more comprehensive look at all possible signatures, precision measurements, and general deviations from expectation

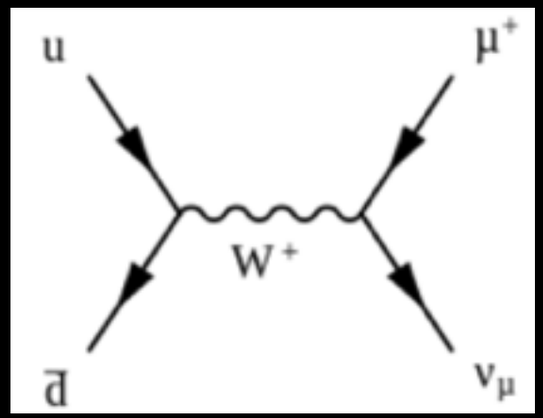
Use generic motivations rather than model-specific ones

LLPs — SM and BSM



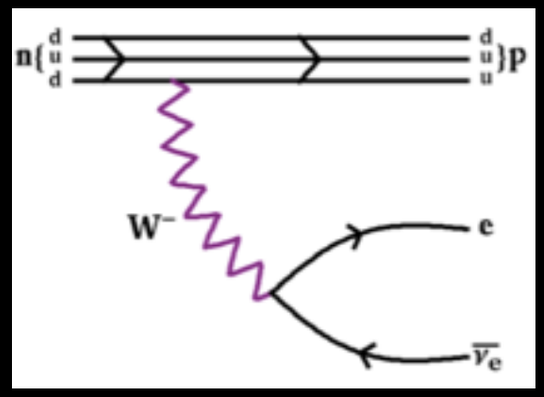
Long lifetimes typically arise in the SM when *approximate symmetries* make the particle stable

Small symmetry-breaking parameters can suppress the decay rate



Charged pion

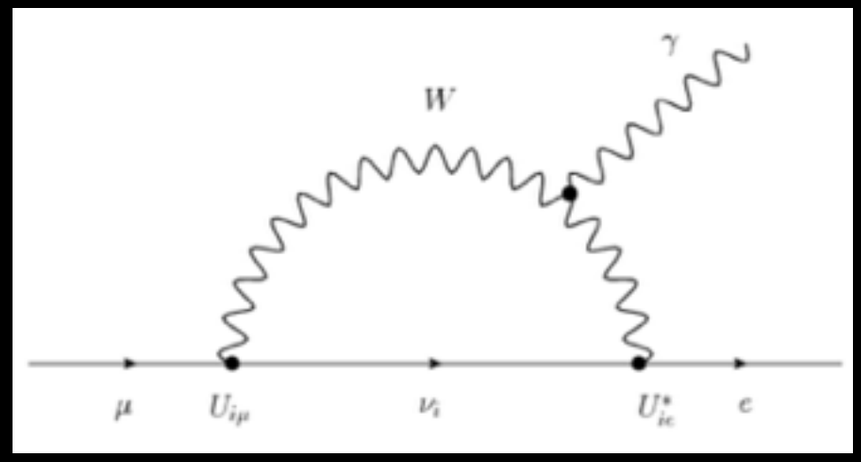
Decay highly off-shell



Neutron

Isospin: p and n nearly degenerate

Decay highly off-shell



FCNC

Lepton flavor violated only by extremely small neutrino Yukawas

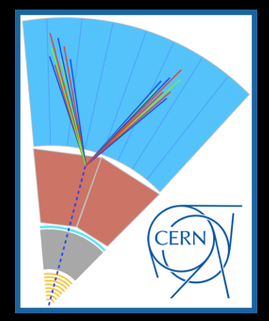
BR(μ—>eγ)~10^{-54}

Same principles apply to BSM LLPs, which can generically appear

- Lifetime is usually best treated as a free parameter

Talks by Strassler, Knapen, Shuve, Ramsey-Mulsof, others

Experiment-focused approach



LLPs can be a generic feature of BSM ideas

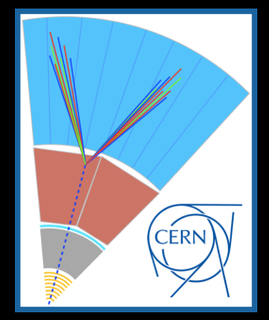
- Lifetime is usually best treated as a free parameter
- No clear old-school preferential motivations w.r.t. production and decay modes

This is good news for signature-minded experimentalists, because it means that particles can decay in various subsystems of the detector with impunity! This means a large number of intriguing, non-standard detector objects and often difficult triggering strategies.

The bad news is that this this means a large number of challenging, non-standard detector objects and difficult triggering strategies. But "bad" in this case just means we need to think critically about the large space of production and decay modes and detector objects.

This is the fun part.

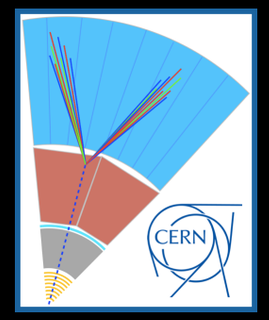
The LHC LLP Community



Signature first, model second

- General classes of motivations that can give rise to LLPs are many
  - Dark photons
  - Hidden valleys
  - R-parity violating supersymmetry
  - Dark QCD-like sectors
  - Heavy neutral leptons
  - Etc.

The LHC LLP Community



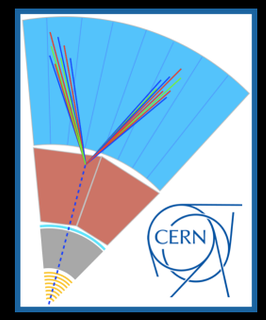
Signature first, model second

- General classes of motivations that can give rise to LLPs are many
  - Dark photons
  - Hidden valleys
  - R-parity violating supersymmetry
  - Dark QCD-like sectors
  - Heavy neutral leptons
  - Etc.

Neutral, stable particle = MET —> dark matter!

- Plenty of well-understood DM searches exploiting prompt objects —> not the explicit focus of this group, but DM is one of many general motivations for LLP simplified models, leading to some natural synergies with the DMWG

The LHC LLP Community Initiative



...in collaboration with the theory/pheno community and MoEDAL, SHiP, milliQan, MATHUSLA, FASER, Codex-b, etc.

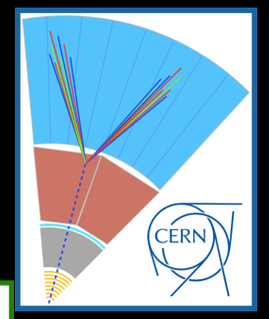
Continuing the work begun by several workshops

- "LLP Signatures" — UMass — Nov. 2015
- "Experimental Challenges" — KITP — May 2016
- LHC LLP Mini-Workshop — CERN — May 2016
- Searches for LLPs at the LHC: First Workshop of LHC LLP Community — CERN — April 2017
- Searches for LLPs at the LHC: Second Workshop of LHC LLP Community — ICTP — October 2017

One question:

How do we best ensure that we don't miss BSM LLP signatures for the remainder of the LHC program?

Experimental signature based focus



Searches for long-lived particles at the Large Hadron Collider at CERN

October 18, 2017

Emmy Noether *Bryn Mawr College, Pennsylvania, USA*

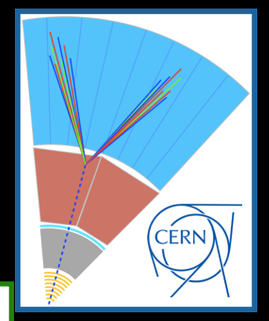
Contact editors: lhc-llp-admin@cern.ch

Simplified model proposal organized around generic classes of LLP production and decay mode, always with an eye toward what the detectors might be able to do

Essentially done.

Contents

Experimental signature based focus



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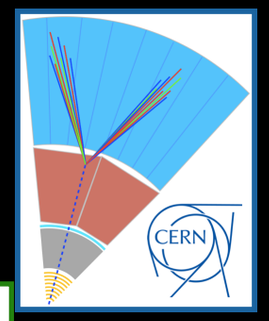

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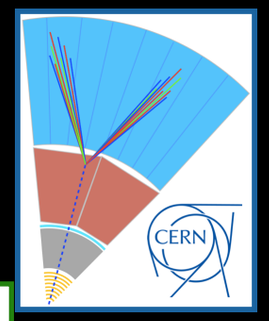
Contents

Experimental coverage: How well do the existing searches cover the parameter space?

Advanced: On track for end-of-year.

Experimental signature based focus



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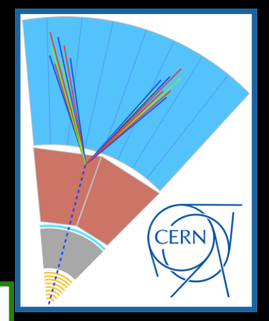

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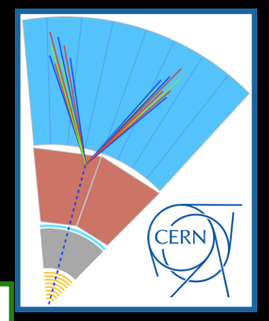
Contents

What triggers are missing? What upgrade studies should be done to advocate for new detector components?

Long-term discussion, to be addressed here and in the future.

Experimental signature based focus



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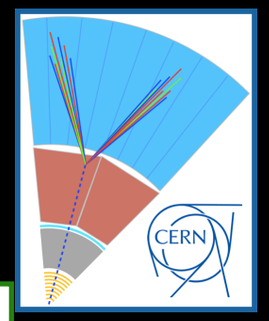

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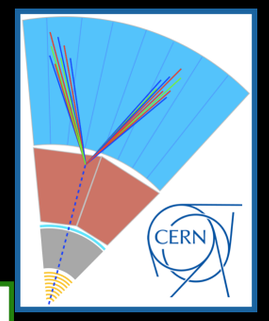
Contents

How should we present our results to ensure optimal re-interpretation and re-cast-ability?

Advanced: On track for end-of-year.

Experimental signature based focus



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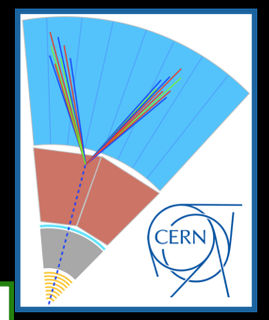

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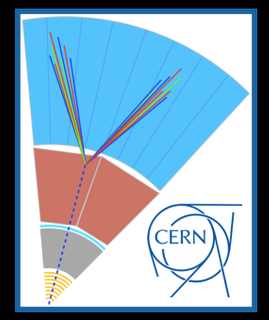
Contents

QCD-like (more or less) dark sectors: What kinds of experimental signatures are between emerging jets and SUEP?

Longer-term work on uncharted territory; still examining how we know what we don't know.

LHC LLP sub-WGs



WG 1: Simplified models

- Previous slides

WG 2: Experimental coverage & recommendations for new searches

- What gaps in coverage exist that should motivate new, improved, and/or expanded searches?

WG 3: Triggers, detector upgrades, and HL- / HE-LHC

- A few concrete, missing triggers in CMS and ATLAS were identified at the April workshop. What studies have been performed to support possible detector upgrades that would improve sensitivity to LLP signatures? What about the prospects, challenges, and opportunities with a high luminosity or a high energy (~25 TeV) LHC? New, blue-sky ideas mandatory.

WG 4: Re-interpretations & recommendations for the presentation of search results

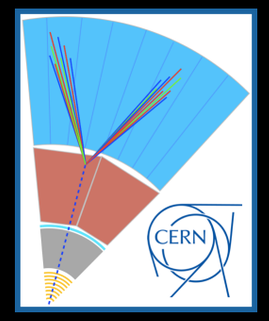
- How do we make sure the published searches are optimally useful in the future? What optimal set of information should be presented in experimental search results? How do we encourage the collaborations to archive their analyses in a way that will enable the future production of accurate, robust, and experiment-controlled re-casting?

WG 5: Dark showers

- How do we address dark sectors with hadronization in a more detailed and comprehensive way, and what does this mean for the current searches in the experimental collaborations for this class of models?

Simplified model proposal

Motivtation classes from the white paper



- **Supersymmetry-like theories (SUSY).** This category contains models with multiple new particles carrying SM gauge charges and a variety of allowed cascade decays. LLPs can arise as a result of approximate symmetries (such as R-parity [15] or indeed SUSY itself in the case of gauge mediation [16]) or through a hierarchy of mass scales (such as highly off-shell intermediaries in split SUSY [17], or nearly-degenerate multiplets [1, 2], as in anomaly-mediated SUSY breaking [3]). Our terminology classifies any non-SUSY models with new SM gauge-charged particles, such as composite Higgs or extra-dimensional models, under the SUSY-like umbrella because of the prediction of new particles above the weak scale with SM charges. In this category, LLP production is typically dominated by SM gauge interactions, whether of the LLP itself or of a heavy parent particle that decays to LLPs.

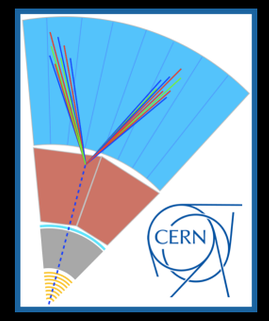
- **Higgs-portal theories (Higgs).** In this category, LLPs couple predominantly to the SM-like Higgs boson. This possibility is well-motivated because the SM Higgs field provides one of the leading renormalizable portals for new gauge-singlet particles to couple the SM, and the experimental characterization of the Higgs boson leaves much scope for couplings of the Higgs to BSM physics [18, 19]. The most striking signatures here are exotic Higgs decays to low-mass particles [20] (as in many Hidden Valley scenarios [4, 5]), which can arise in models of neutral naturalness [21–23] and dark matter [24]. The Higgs is also special in that it comes with a rich set of associated production modes in addition to the dominant gluon fusion process, with vector-boson fusion (VBF) and Higgs-strahlung (VH) production modes allowing novel opportunities for triggering on and suppressing backgrounds to Higgs-portal LLP signatures.

- **Gauge-portal theories (ZP).** This category contains scenarios where new vector mediators can produce LLPs. These are similar to Higgs models, but where the vector mediator is predominantly produced from $q\bar{q}$-initiated final states without other associated objects. Examples include models where both SM fermions and LLPs carry a charge associated with a new Z' (for a review, see Ref. [25]), as well as either Abelian or non-Abelian "dark" photon or dark Z models [26] in which the couplings of new vector bosons to the SM are mediated by kinetic mixing. Scenarios with LLPs coupled to new gauge bosons are well motivated by theories of dark matter, particularly models with significant self-interactions [27–29] and/or sub-weak mass scales [30–34].

- **Dark-matter theories (DM):** Non-SUSY and hidden-sector DM scenarios are collected in this category, which encompasses models where the cosmological dark matter is produced as a final state in the collider process. The main feature distinguishing this category from the Higgs and gauge scenarios above is that dark matter, i.e., missing transverse momentum ($\not{E}_T$), is a necessary and irreducible component of such signatures [4, 5, 10, 11, 35–40].

- **Heavy neutrino theories (RHν):** Models where new weak-scale states are responsible for SM neutrino mass generation [41–44] typically predict long-lived TeV-scale right-handed neutrinos that can be probed at the LHC [45, 46]. Characteristic features of models in this category are singly-produced LLPs via SM neutral and charged current interactions, and lepton-rich signatures.

Simplified model proposal and DM



Production \ Decay	$\gamma\gamma$(+inv.)	γ + inv.	jj(+inv.)	$jj\ell$	$\ell^+\ell^-$(+inv.)	$\ell^+_\alpha\ell^-_{\beta\neq\alpha}$(+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 $\to XX$ + inv.	Higgs, DM*		Higgs, DM*		Higgs, DM*	
HIG: $h \to X$ + inv.	DM*		DM*		DM*	
ZP: $Z(Z') \to XX$ or $\to XX$ + inv.	Z', DM*		Z', DM*		Z', DM*	
ZP: $Z(Z') \to X$ + inv.	DM		DM		DM	
CC: $W(W') \to \ell X$			RHν*	RHν	RHν*	RHν*

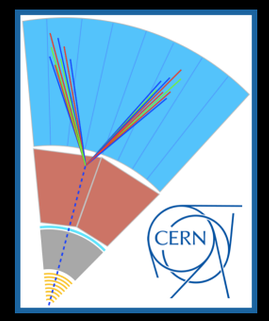
Table 2.1: **Simplified model channels for neutral LLPs.** The LLP is indicated by X.

"DM" here is a generic class of motivations

Our simplified model space is built to span signatures from all kinds of motivations ranging from naturalness to dark sectors to neutrino mass models, and so we basically avoid talking about UV models or cosmological implications entirely

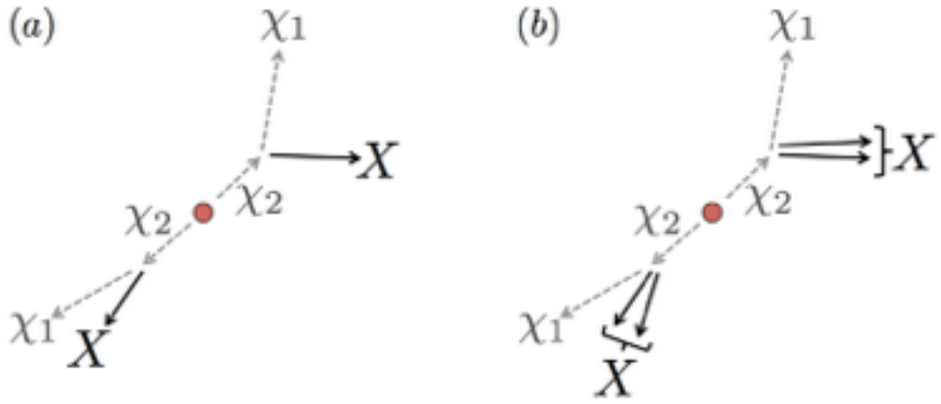
- A natural interface with the DMWG could be to create a task force / study group to 1) discuss the cosmologically sanity of such models and 2) map out the coverage specifically in DM model space compared to other searches
- E.g., the standard reminder: "The right relic abundance" shouldn't be taken too seriously

DM and LLPs: Existing nice example



Signatures

What are the typical signatures we expect for neutral long-lived particles?



- Missing Energy.
- Pairs of displaced vertices.
- Non-pointing collider objects.

Matt McCullough

A great example of some robust thought in this direction is Buchmueller, De Roeck, McCullough, Hahn, Sung, Schwaller, Yu (see Tien-Tien's talk)

In Practise

Matt McCullough

Add new long-lived particle to existing models for particle production. E.g.

Simplified DM Models		
Variables	DM candidate	Interaction
m_ϕ	Dirac	Vector
m_1	Majorana	Axial-Vector
g_χ	Scalar-real	Scalar
g_ϕ	Scalar-complex	Pseudoscalar
Displaced Signature Extension		
τ , m_2	Decay of $\chi_2 \to \chi_1 X$	

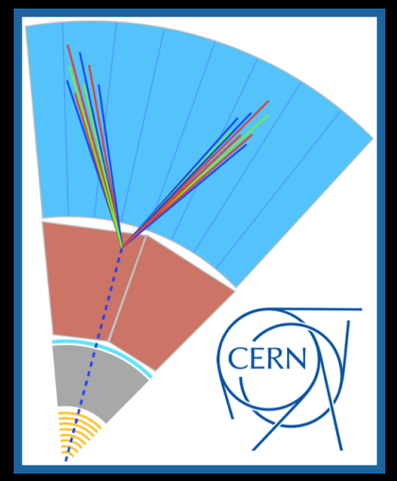
Generate events with MadGraph: $pp \to \chi_2\chi_2$

And decay with, e.g. PYTHIA: $\chi_2 \to \chi_1 + X$

Explored some simplified models for neutral LLPs in the context of well-known DM motivations, ideas and mediators

arXiv:1704.06515

The LHC LLP Community



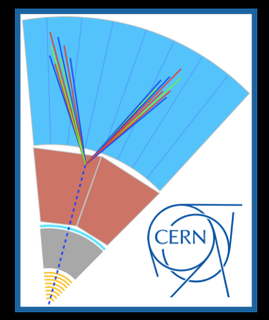
White paper to appear in the spring

- Draft chapters either finished or coalescing now (this week), giving Brian and I some winter homework
- Collected knowledge and recommendations, elucidating uncovered searches, gaps in coverage from general simplified model classes, recommendations for presentation of search results, high priority HL/HE studies to be done, and implications for the future

LHC LLP Community moving forward

- Twice yearly workshop schedule, spring (likely here at CERN) and fall (TBD)
- New LLP ideas, new signatures, improvements in coverage, evolving high-priority searches and studies, etc.
- Simplified models are just that, simplified, so already some organic interest in studying some of the classes of motivations in detail, leveraging the strength of the community
  - HNL enthusiasts have already started a study group / task force to do this for displaced heavy neutrino signatures
  - DM version of this would be ideal!

The DMWG and the LHC LLP Community



Ideas for synergies

- Possible DM-LLP task force / study group
  - Discuss the cosmologically sanity of the LHC LLP DM-related simplified models
  - Map out the coverage specifically in DM model space compared to other searches

- Where do existing searches (both w/ and w/o MET) gain and lose sensitivity in well-oiled and complete DM models?
  - Natural exchange with our LHC LLP Experimental Coverage WG

- Is there anything missing in how some LLP searches are presented that could be of great interest to the DM-specific community?
  - Natural exchange with LHC LLP Re-interpretations/Recommendations WG

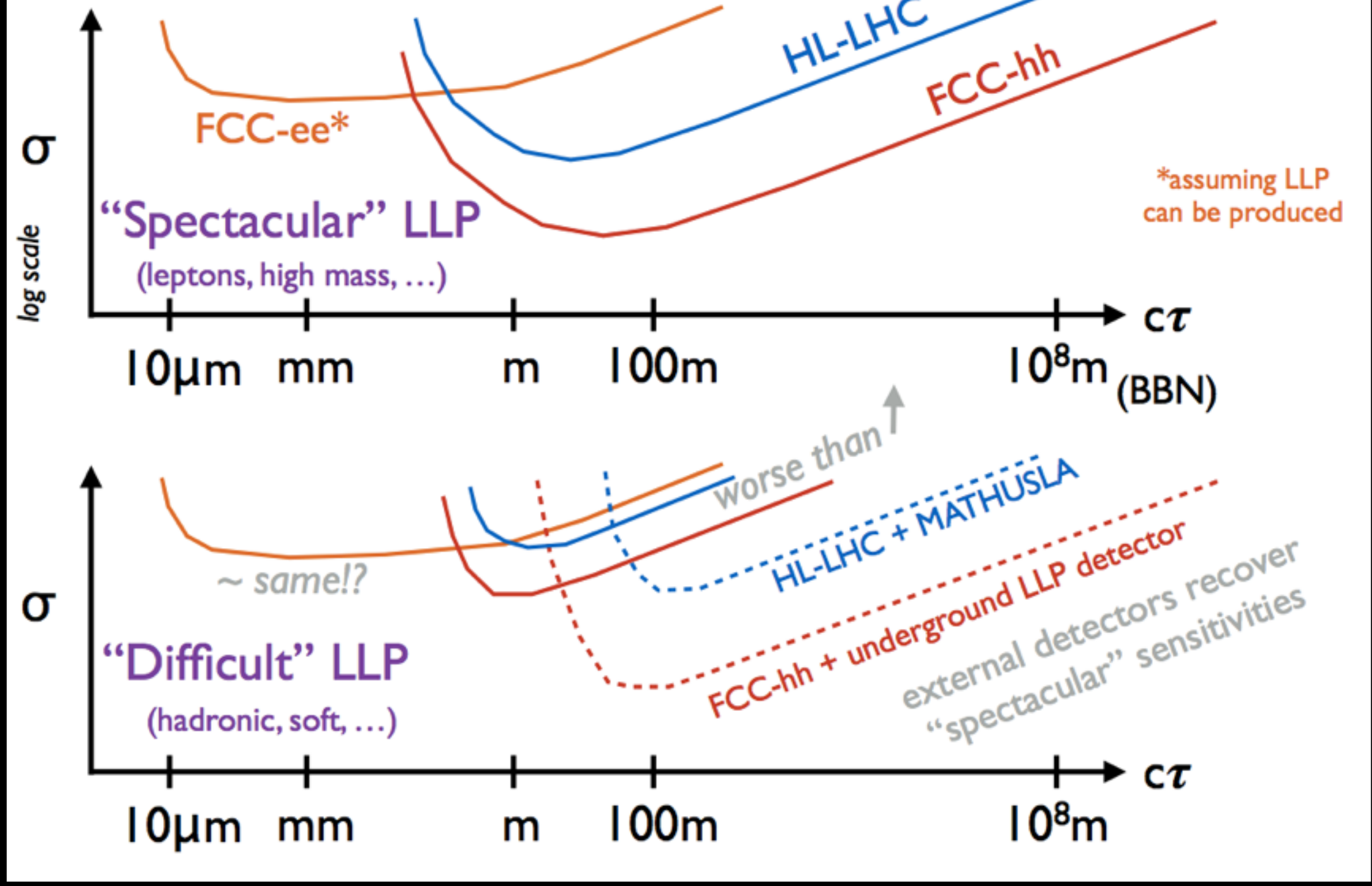
- What about dark showers?
  - Pedro, et al., well equipped to think about this in the context of DM, but could perhaps be a place of greater discussion?
  - Emerging jets (pencil-like objects) vs. soft, unclustered energy patterns (SUEP) vs. semi-visible jets (one corner of in-between) vs. ongoing in-between work; what about the mediators in these scenarios?

One might envision a one-day mini-workshop devoted to discussing these ideas and more

END

Reserve slides

★Cartoon★ of relative LLP sensitivities



D. Curtin