Gaps in LLP coverage

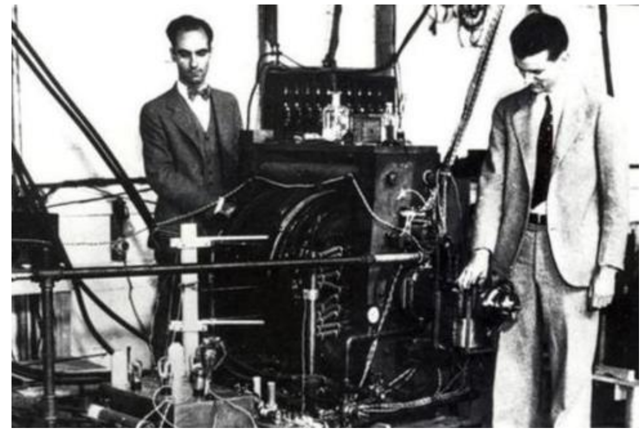
David Milstead

Stockholms Universitet

Some overlap but not a repetition of the excellent white paper: arxiv: 1903.04497

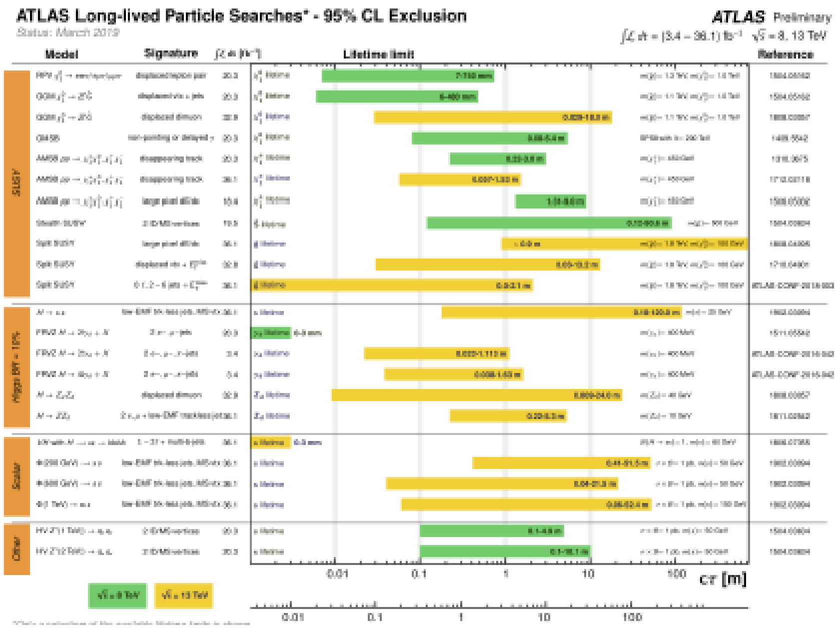
Particle physics discoveries

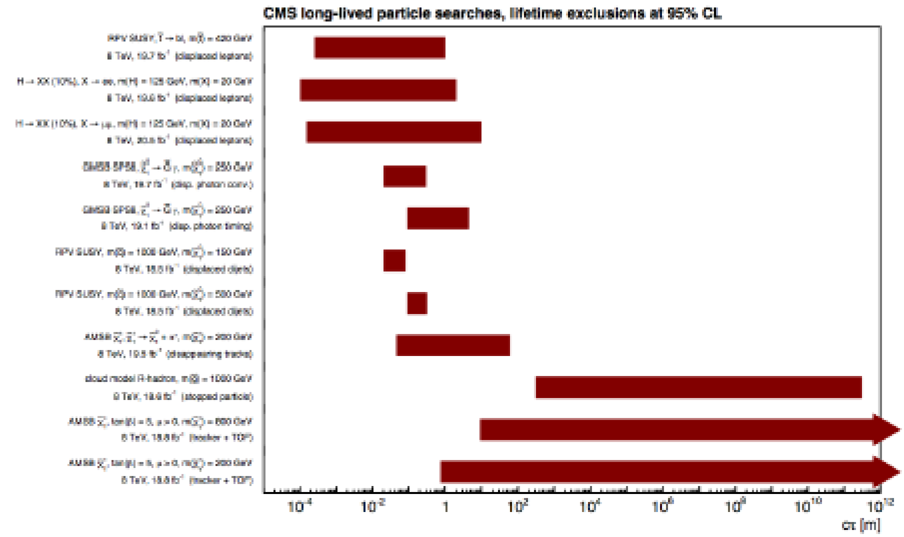
- Falsifiable prediction of unfalsified model: Eg Higgs.
- ”Who ordered that ?” . Eg muon.

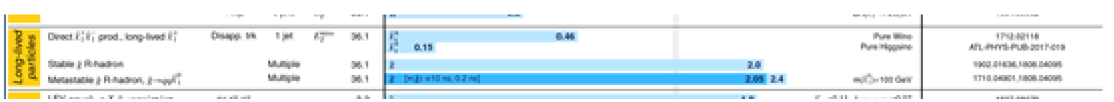


- Searches based on ”well motivated” BSM models must be done and (generally) are being done.
  – But they haven’t yet worked out and may well not do so.
- Blue sky/signature searches require us to jump over the ”why bother ?” hurdle.
  – Not always easy

Long-lived particles searches







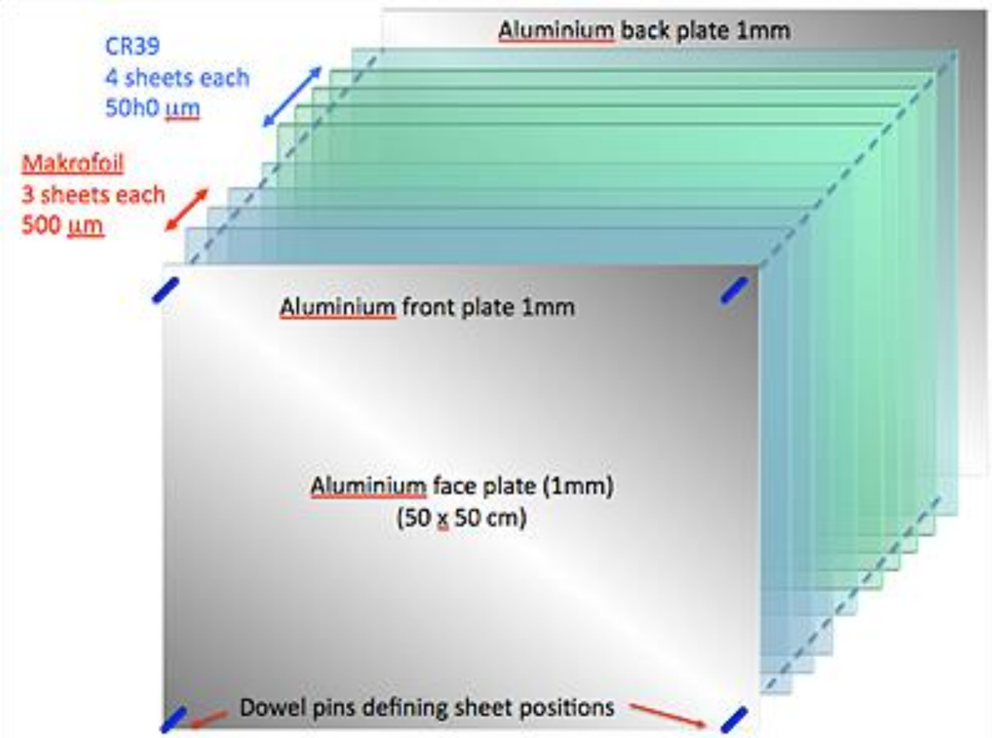
Many searches, some theory-led, some ”blue sky”.
Direct LLP measurement, displaced vertex, out-of-time decays+indirect searches.
Great new projects: Faser, MilliQan , Mathusla, Codex-b..
Focus mainly on direct non-decaying LLP searches at running expts.
Are we covering the full ”blue-sky” range ?

Sensitivity for LLPs with known charge quantum numbers

Electric charge/e	Magnetic charge/g_d	Colour charge	Expt.
0	1-5	$\overline{1}$	ATLAS,CMS,Moedal ($Z/\beta \sim 5$)
1	0	$\overline{1}$	ATLAS, CMS,LHCB…
1-8, 8-100	0	$\overline{1}$	ATLAS+CMS
wide	wide	$\overline{1}$	Moedal ($Z/\beta \sim 5$)
wide	0	$\overline{1}$	Moedal ($Z/\beta \sim 5$)
0.001-0.1	0	$\overline{1}$	MilliQan
1/3,2/3	0	$\overline{1}$	ATLAS+CMS
1/3,2/3	0	$\overline{3}$	ATLAS+CMS
0	0	$\overline{8}$	ATLAS+CMS

Wide coverage in charges.
Mass sensitivity depends on assumed production mechanism/calculation

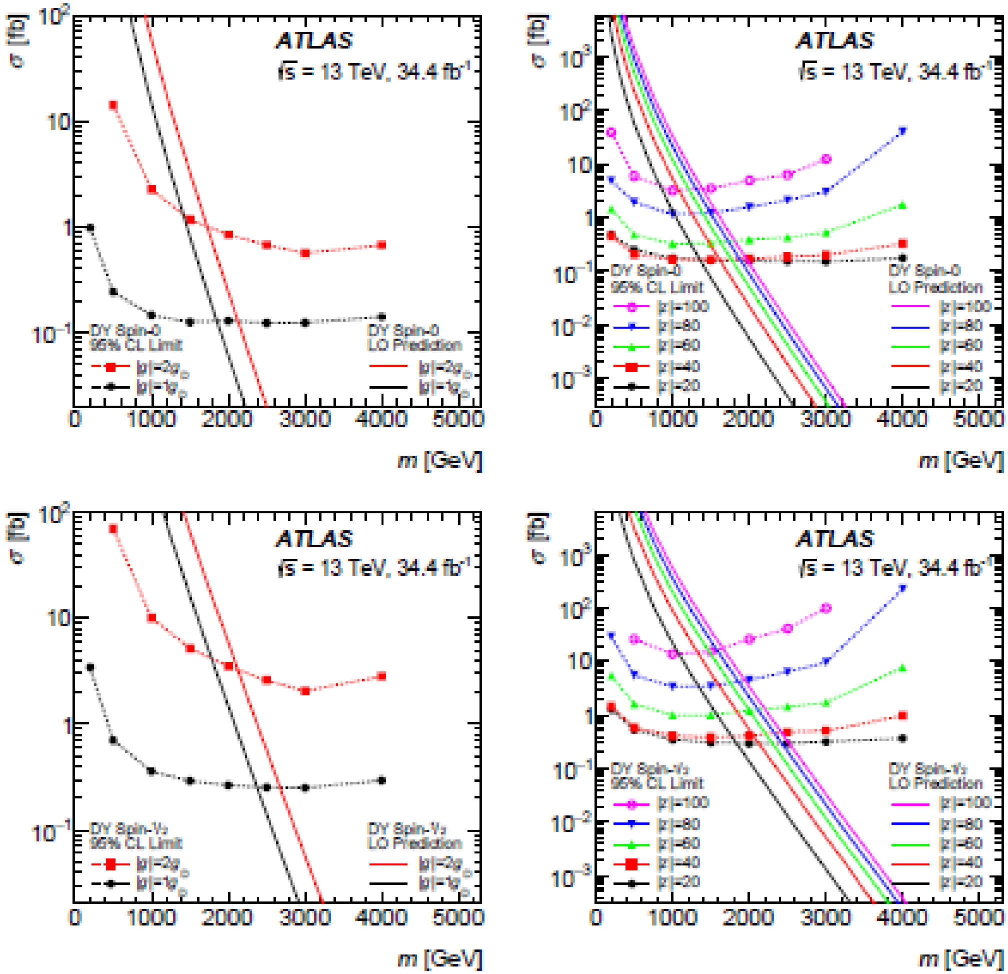
Anomalous electric charge



Missing 8-20e, >100e . Moedal can plug gaps.

What is the upper limit in sensitivity ?

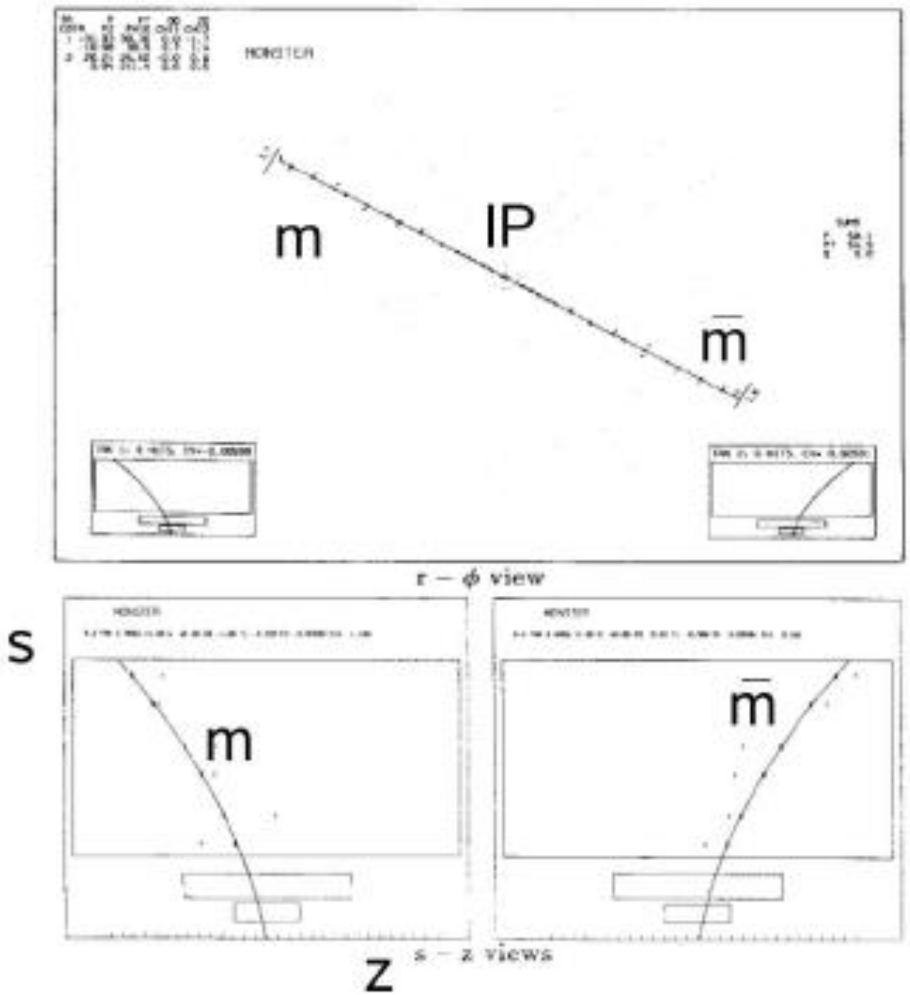
Magnetic and electric charges



Missing dedicated searches for LLPs with magnetic and electric charges (Moedal is capable).

Colour won't make too much of a difference but would change limits.

Monopole charge



Tasso

Searches tend to assume ng_D

$n = 1, 2, 3...$

Moedal below $< n$

What is the sensitivity limit ?

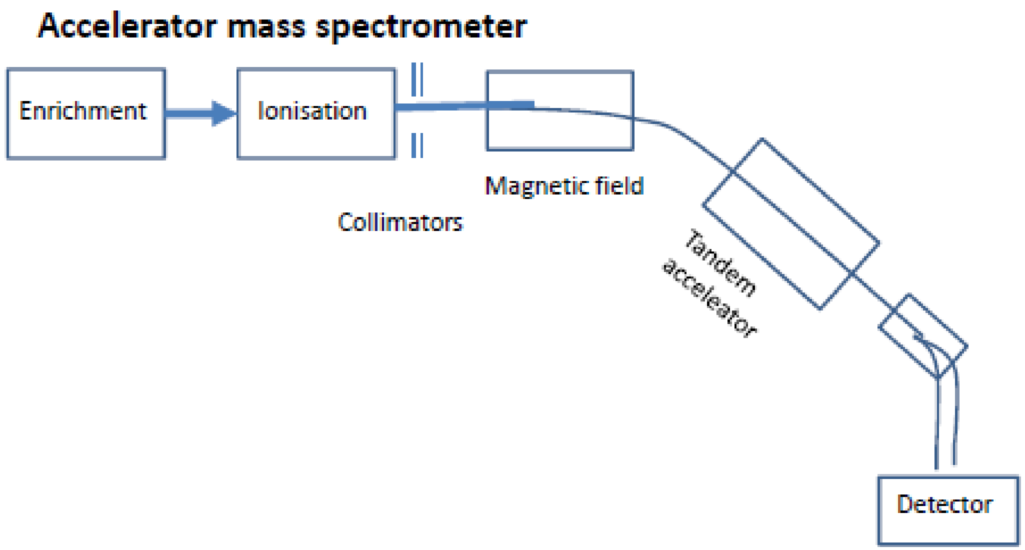
How can this be supplemented with track-based searches ?

Belle-2 but also should be done for higher masses (LHC).

What if ?

- The LLP is produced with an unexpected momentum/speed (eg β~0.1) or charge (eg 300e) and never makes it into the detector.
- Heavy stable particle trapped in inactive matter.
- For monopoles, the induction technique is used.
- For electrically charged particles other methods to be used.

Searching for anomalous heavy isotopes



Enrichment (sputtering), vaporisation and ionisation.
Separation by magnetic field and tandem accelerator.

Searching for anomalous heavy isotopes

Sample	Method	SMP	Mass range (GeV)	Concentration limit	Ref.
D_2O	MS	X^+	$6-16$	$3 \cdot 10^{-18}$ (H)	[260]
D_2O	MS	X^+	$6-350$	$4 \cdot 10^{-22} - 2 \cdot 10^{-21}$ (H)	[263]
D_2O	MS/TOF	X^+	$12-1200$	$2 \cdot 10^{-29} - 2 \cdot 10^{-28}$ (H)	[264]
H_2O	spectroscopy	X^+	$10^4 - 10^7$	$6 \cdot 10^{-15}$ (H)	[266]
H_2O	MS/TOF	X^+	$5-1600$	$4 \cdot 10^{-17}$ (H)	[267]
H,D	MS	X^+	$0.3-8$	$2 \cdot 10^{-19} - 10^{-13}$ (H)	[261]
D,Li,Be, B,C,O,F	MS	X	$10^2 - 10^4$	$10^{-23} - 10^{-9}$ (nucleon)	[265]
He,Ar	MS	X^{++}, X	$42-82$	$2 \cdot 10^{-12} - 2 \cdot 10^{-11}$ (nucleus)	[281]
He	spectroscopy	X^{++}, X	$20-10^4$	$10^{-17} - 10^{-12}$ (nucleus)	[283]
Na	spectroscopy	X	$10^2 - 10^5$	$7 \cdot 10^{-12}$ (nucleon)	[272, 273]
lunar soil	MS	X	$42-70$	$6 \cdot 10^{-17} - 5 \cdot 10^{-12}$ (nucleus)	[278]
O	MS	X	$20-54$	10^{-16} (nucleon)	[271]
chondrites, nickel ore, lunar soil	activation	strangelet	$2 \cdot 10^3 - 10^8$	$4 \cdot 10^{-17} - 10^{-13}$ (nucleon)	[279]
Au	MS	X	$< 1.7 \cdot 10^3$	$6 \cdot 10^{-12} - 10^{-8}$ (nucleus)	[282]
meteorite	MS	X	< 647	$6 \cdot 10^{-9} - 10^{-8}$ (nucleus)	[282]
Rn	gamma	X	~ 150	10^{-29} (nucleus)	[270]
C	radiochemistry	X^-	$< 10^5$	$2 \cdot 10^{-15}$ (nucleon)	[285]
Fe	radiochemistry	X^-	$< 10^4$	$2 \cdot 10^{-12}$ (nucleon)	[275]
Pb	radiochemistry	X^-	$< 10^4$	$3 \cdot 10^{-13}$ (nucleon)	[276]
Pu, meteorites, sediments	back scattering	X	$4 \cdot 10^2 - 10^7$	$10^{-17} - 10^{-11}$ (nucleon)	[286]

TABLE I. Summary of limits on SIMP abundances in Au and Fe. For each of the geological samples in the left column, we present the estimated exposure time in millions of years (Myr). We also present the mass range for anomalous isotopes X covered by each sample, and the 95% C.L. limits on the abundance ratios, X/Au and X/Fe, for the Au and Fe samples. See text for further details.

Sample	Exposure age [Myr]	Mass range [GeV/c^2]	Limit range
Laverton	1.25	188–1669	$X/\mathrm{Au} < 6.3 \times 10^{-12}$–$1.1 \times 10^{-8}$
Nullagine	1.25	188–647	$X/\mathrm{Au} < 7.5 \times 10^{-11}$–$2.7 \times 10^{-9}$
Arizona	0.02–0.4	188–1669	$X/\mathrm{Au} < 8.9 \times 10^{-12}$–$1.5 \times 10^{-8}$
Golden Valley, NC	0.1–0.2	188–1669	$X/\mathrm{Au} < 6.5 \times 10^{-12}$–$1.1 \times 10^{-8}$
Black Run Creek, NC	0.1–0.2	188–647	$X/\mathrm{Au} < 6.6 \times 10^{-11}$–$2.4 \times 10^{-9}$
LDEF	⋯	188–1669	$X/\mathrm{Au} < 6.6 \times 10^{-12}$–$1.1 \times 10^{-8}$
RHIC	⋯	188–1669	$X/\mathrm{Au} < 6.2 \times 10^{-12}$–$1.0 \times 10^{-8}$
Meteorite	540	188–647	$X/\mathrm{Au} < 5.6 \times 10^{-9}$–$9.7 \times 10^{-9}$

D. Javorsek et al. PRL 87 (2001) 231804

Au into a beam dump at RHIC.

Other techniques with trapped LLPs

- Rutherford back scattering (238U)
- Heavy ion activation followed by photon emission

- Eg Strangelets
- Meteorites, nickel, lunar soil

Table top experiment for stopped SMPs

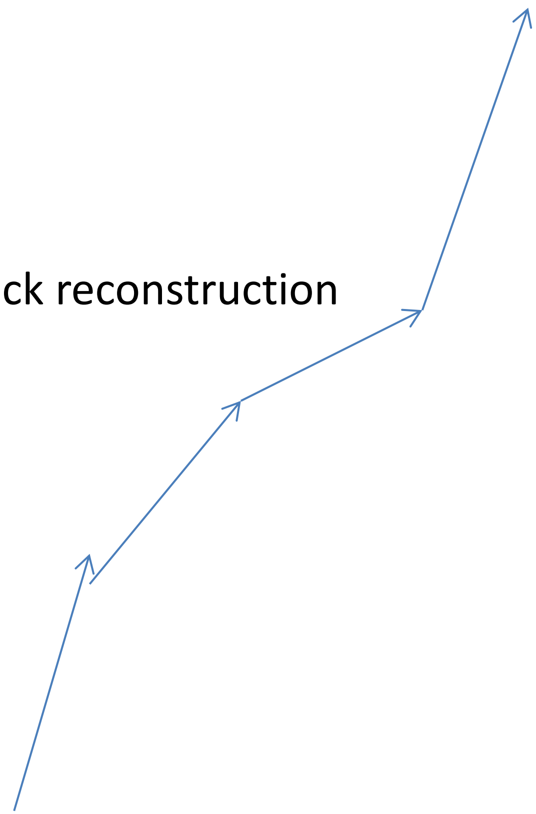
- Finding equipment used in another field and which is already calibrated and ready to use.
- Persuading CERN to hand over material which may be enriched in LLPs.
- Several weeks work.

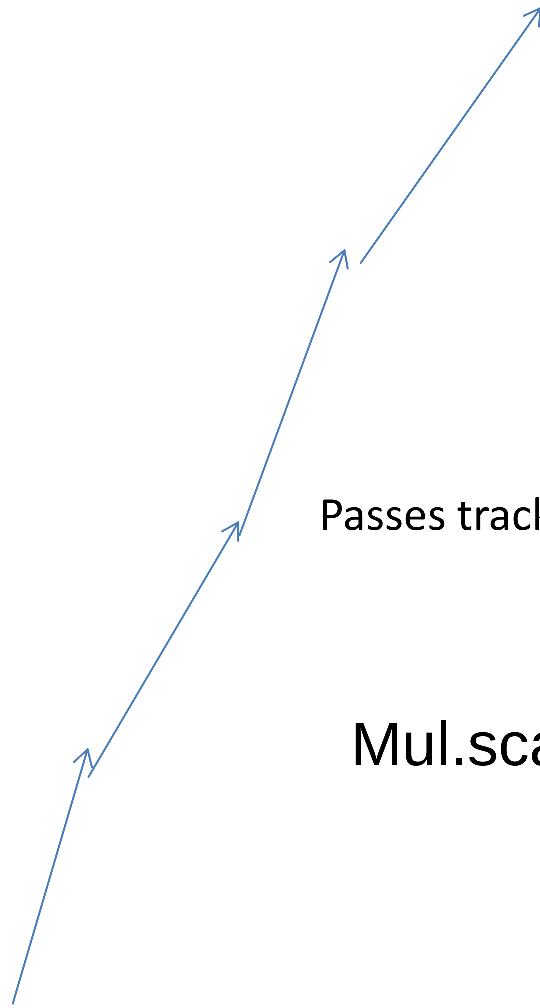
What if ?

- The LLP passes through the detector but interacts in a way which is unexpected ?
- Would our trigger and track/calo reconstruction algorithms work ?

Particle scattering

Fails track reconstruction





Passes track reconstruction

$$\text{Mul.scatt.} + {}^{k}\!/_{\beta p}$$

Multiple scattering for heavy particles is understood.
As long as there aren't interactions with matter which we don't know about.

Other non-standard trajectories/tracking

- Disappearing tracks
- Strongly interacting massive particles
- Charge flipping (R-hadrons, quirks)
- …

Event property searches

- Detectors are now far better understood than at the LHC turn-on.
- Study number of delayed hits in an event
  - in geometric regions.
- Sensitivity to non-reconstructed LLPs ?
- Sensitivity to decay products from slow LLPs which may themselves interact in an unexpected way ?

There are many holes

1. All-hadronic LLP decays

- Associated-object triggers (especially motivated by Higgs-like VBF and VH production modes) need to be more comprehensively used to improve sensitivity to low-p_T objects.
- Improvements are needed in sensitivity at lower masses & lifetimes (e.g., for LLPs produced in Higgs decays).
- Single hadronic DVs need to be looked for in searches that currently use two (such as decays in ATLAS HCAL and MS).
- Possibilities need to be explored for ATLAS and CMS for online reconstruction of hadronic displaced objects, as the inclusive H_T triggers used by the two collaborations miss these objects unless they have a large p_T. (By constrast, LHCb can trigger on a displaced hadronic vertex [246, 247].)
- Low-mass hadronically decaying LLPs can look somewhat like tau leptons, so the question remains as to whether there is any possibility of using, for example, L1 tau triggers to seed displaced jet triggers at HLT and improve trigger efficiency; studies need to be performed by the experimental collaborations.
- The prospects for dedicated searches for displaced hadronic taus need to be investigated, since no dedicated searches currently exist.
- The potential for flavor-tagging displaced jets (b-displaced jets, c-displaced jets, etc) needs to be explored.

2. Leptonic

- Coverage needs to be provided for the intermediate region between boosted, low-mass LLPs (lepton jets) and high-mass, resolved LLPs (resolved ATLAS/CMS searches).
- Improvements need to be made to extend coverage to lower masses and to lower p_T thresholds. Currently no prescription or plan for this exists, and so dedicated studies need to be done.
- Searches need to be done for different combinations of charge and flavor of displaced leptons (e.g., same-sign vs. opposite-sign, opposite-flavor vs. same-flavor).
- Searches need to be done for tau leptons in LLP decays, in particular if they come from the ID; an unanswered question remains as to whether displaced-jet triggers can be used for this purpose.

3. Semi-Leptonic

- Searches do not exist and need to be done for LLP masses below about 30 GeV; this mass range is theoretically well motivated by Majorana neutrinos.
- Searches need to be performed for all flavor combinations (for example, one CMS search only covers $e^{\pm}\mu^{\mp}$), as well as same-sign vs. opposite-sign leptons.
- Currently unknown improvements need to be made to relax or modify isolation criteria wherever possible to recover sensitivity to boosted semi-leptonic decays.
- Searches need to be done that better exploit triggering on associated objects for improved sensitivity to low-mass objects, or to employ high-multiplicity lepton triggers if there are multiple LLPs.

4. Photonic

- There is currently no coverage for LLPs decaying into $l\gamma$, $j\gamma$, or without $\not{E}_T$, and searches urgently need to be performed for this decay topology.
- There is currently poor coverage (i.e., there exists no dedicated search) for single-γ topologies. The only searches with sensitivity require two jets to be present in addition to $\not{E}_T$ [296]. Studies are needed to assess the sensitivity of this search to signals with only one delayed photon and different jet multiplicities.
- There is currently no coverage for softer non-pointing or delayed photons, and searches need to be performed for these kinematic realms.
- Studies need to be performed to determine if triggers on associated objects may improve sensitivity to signals with a single photon, without $\not{E}_T$, or for lower-p_T photons

5. Other exotic long-lived signatures

- Disappearing tracks with $c\tau \sim$ mm are very hard to probe, and new ideas and detector components are needed to extend sensitivity to this potential discovery regime. It's unclear if the ATLAS insertable B-layer will be present in HL-LHC run and how sensitivity to the disappearing track topology will improve with the replacement of the current inner detector with the new ITk (Inner Tracker), or whether new tracking layers very close to the beam line can be added. It's an open question as to what is the lowest distance at which new layers (or double layers) can be inserted. Another open question that needs to be answered is whether there are any prospects for disappearing tracks at LHCb with an upgraded detector.
- No dedicated searches for quirks exist at the LHC, a huge, open discovery possibility for ATLAS, CMS, and LHCb. Some LHC constraints exist by reinterpreting heavy stable charged particle searches, but dedicated searches need to be performed. There are significant challenges in modeling the propagation and interaction of quirks with the detector, as well as in fitting tracks to their trajectories, but new ideas have been proposed that need to be explored by the experimental collaborations that might allow improved sensitivity to quirks with less ambitious analysis methods.

White paper: arxiv: 1903.04497

Quirks + decays into taus particularly prominent omissions.

LLP and inclusive searches

- At what stage do dedicated LLP searches and inclusive searches run into each other
- Eg R-hadron (neutral only) ~ Monojet + MET
- Which LLP hypotheses are least likely to be seen in high luminosity non-LLP searches ?
- Can this be systematically studied.

Summary

- A very active and interesting program of LLP searches
- Gaps
- Personal observations and request:
  - A better sensitivity to a given scenario should not be pre-requisite for a search in a different collision environment (i.e. expand heavy ions).
  - We still rely on models to a varying degree to justify performing searches.
  - Can we publish a LHC paper in which it is stated: ”We know of no theoretical justification for performing the search for a new particle X with its assumed set of properties. The search is conducted because the experiment has sensitivity to the production of such a particle for the first time”

Long-lived particles

- Long-lived particles were a blue sky/minority pursuit
  - LHC detectors generally not designed with LLPs in mind.
  - Never a good reason for this other than our own expectations
  - Stable long-lived particles + displaced vertices are now accepted as observables which are as fundamental in the LHC search program as MET.