Long Lived Particle Searches
Experimental Considerations

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A little (biased) context

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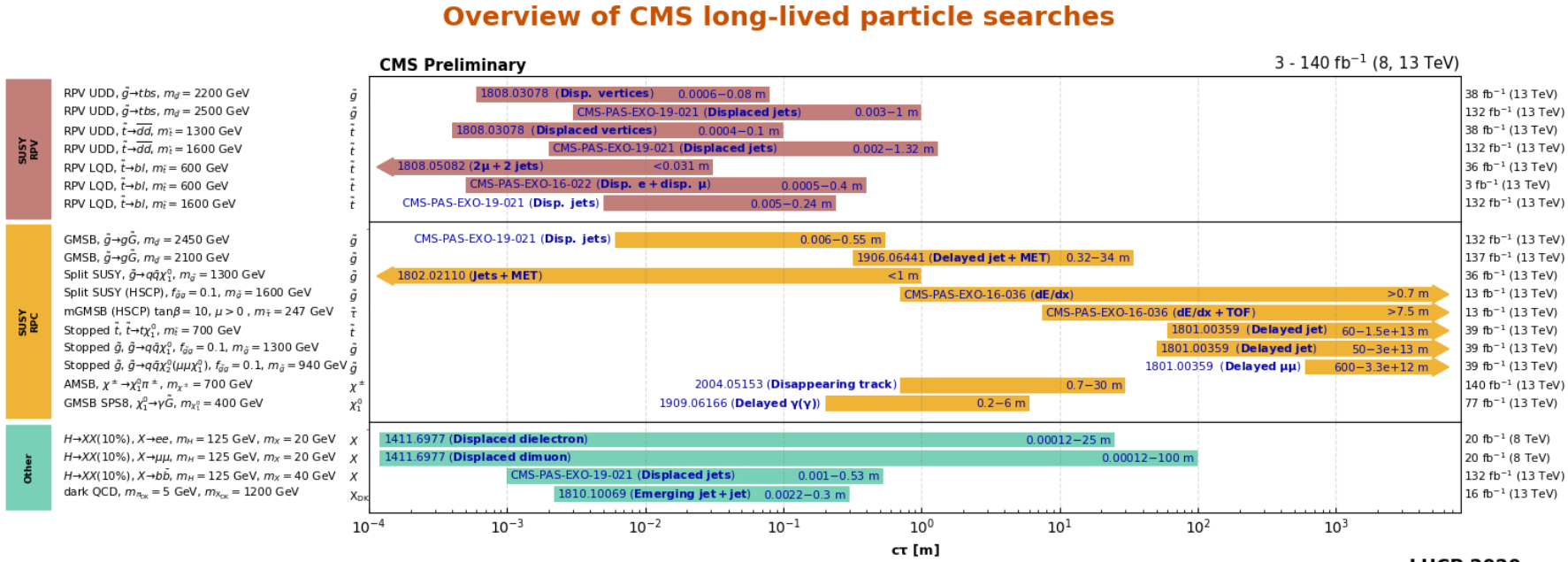
- I was asked to give this talk (I assume) because I have been doing LLP searches for the better part of 2 decades
  - *Long before the recent surge in interest*
  - *Why?*
    - **It has long been my belief one of the best ways to make a discovery is to look where no one has before**
    - **For my LLP searches this has often meant developing new triggers, reconstruction, analysis ideas, and detectors/experiments**
      - *In this way over the years I've developed a suite of techniques that cover the entire relevant lifetime range*
      - *Combined with the work of others, and the increasing popularity of these analyses, the LLP coverage at LHC is now pretty good (see below)*



ATLAS & CMS current LLP programs

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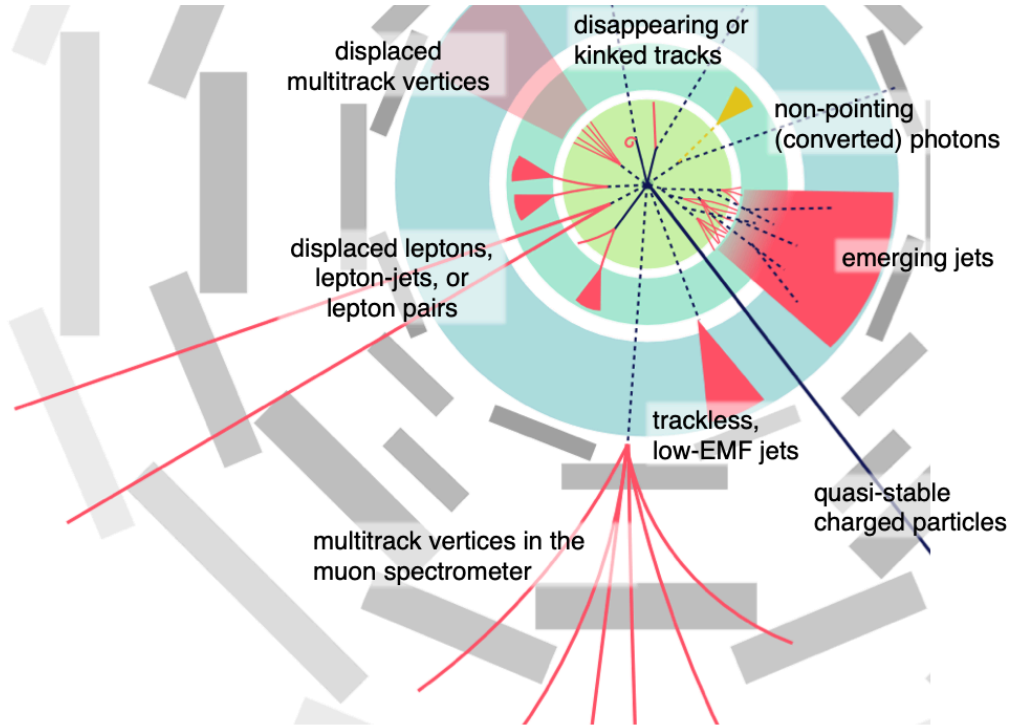
- Utilize different sub-detectors, with different experimental challenges to cover full lifetime range:
  - *Tracker*
    - **Find displaced tracks, vertices**
    - **Find tracks that "disappear" (or kink)**
    - **Use low/high dE/dx information to indicate passage of BSM particle**
    - **ID displaced photons via conversions**
  - *Calorimeters*
    - **Find displaced jets**
    - **Anomalous jets as indication of new force (too few tracks and/or "emerging")**
    - **Stopped particles**
  - *Muon systems*
    - **Highly displaced vertices**
    - **Stopped particles**



N.B. Due to exponential nature of decays combined with finite resolution, short lifetime limit of tracker based analyses **overlap with coverage from prompt searches** (to some extent)

Coverage will be good at HL-LHC too

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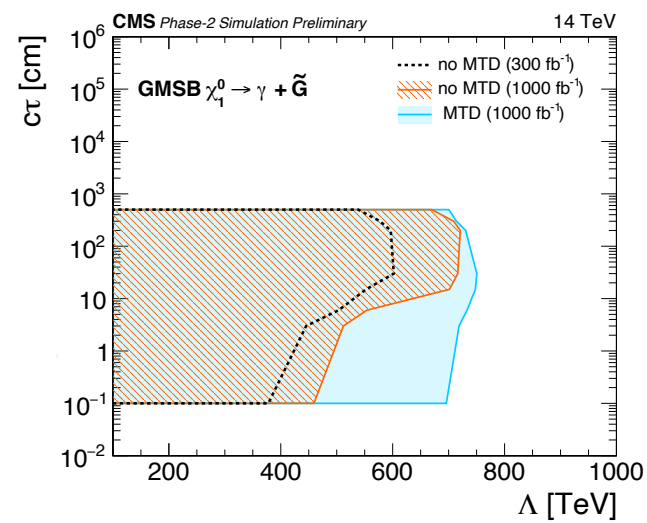
- Due to increased interest, and generally more capable detectors, overall I expect this coverage will be as good or better for the HL-LHC
  - *But while extending reach by repeating existing LLP analyses in the HL-LHC era should certainly be done*
  - *(and there will be a lot of non-trivial work to adapt these to the challenging new environment)*
  - *Some work already done for ESG + TDRs (see examples at right) but Snowmass probably should play a role in also studying this*
    - **However, for the most part this is not looking somewhere no one has before (in the same way that has motivated me in past)**

- Examples from CMS:
  - FTR-18-002: Dark photons to displaced μ
  - https://cds.cern.ch/record/2644533
  - FTR-18-018: L1 track jet trigger for displaced jets
  - https://cds.cern.ch/record/2647987
  - MTD TDR (TDR-19-002)
  – Delayed photons (Section 5.4.2)
  – HSCPs (Section 5.4.3)
  - CMS Muon TDR (TDR-17-003)
  – HSCP with RPC trigger (Section 8.2.2)
  - Tracker TDR (TDR-17-001)
  – HSCPs (Section 6.5.5)



LLP searches are inherently experimental

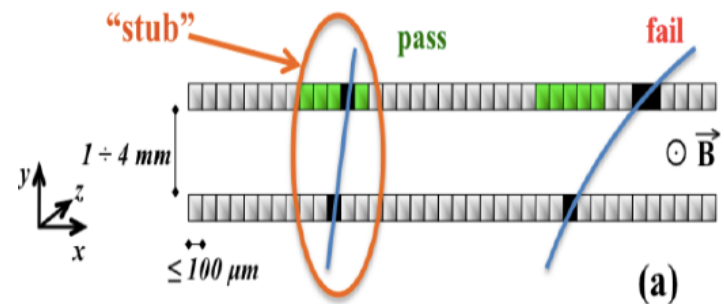
- While it is always inspiring to hear new theoretical ideas that invoke LLPs (as in the previous talk), what LLP searches can actually be done boils down to experimental capability (+ time needed to implement)
  - *There is a balance here, something might be well motivated theoretically but so experimentally difficult that it will never actually happen*
    - **I can give you many such examples**
    - **While Snowmass is the perfect time to explore ambitious ideas, we should be cognizant of the fact that Snowmass studies will not necessarily represent reality**
- The LHC experiments were (for good reasons) not designed for LLPs
  - *This remains true for HL-LHC*
  - *However, both ATLAS/CMS will have new experimental capabilities*
  - *There will even be some new LHC experiments*
    - **IMHO Snowmass LLP studies should focus on how to exploit these to look where we could not before**

e.g. rewriting global tracking to find kind **kinked tracks** anywhere is **ill advised** … they are just disappearing tracks!

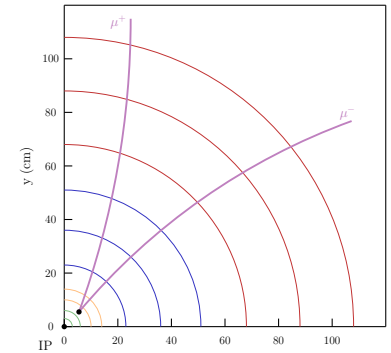
(*S/B is very high so can easily find the kinked track in such an event, possibly even by eye*)

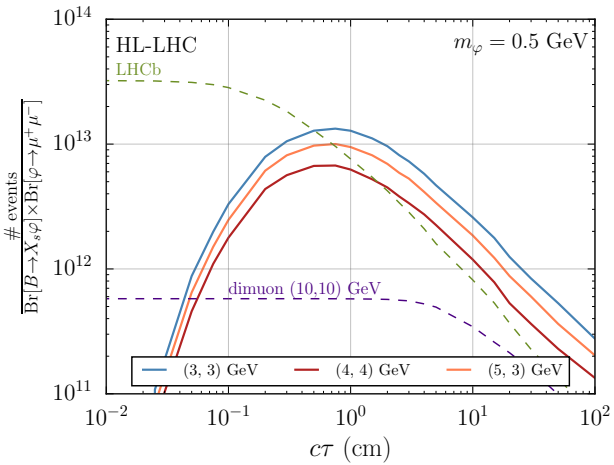
Effect of HL-LHC Tracker Upgrades on LLP programs

- Tracker based signatures will definitely be impacted
  - *Both CMS/ATLAS new trackers with some degree of new triggering capability*
    - **Triggering is often a limitation of reach of searches with tracker based LLP signatures**
  - *CMS will have triggers seeded at L1 with a track*
    - **No need for ISR triggers for neutral final states (e.g. disappearing tracks)**
    - **Direct triggering on displaced vertices**
    - **Potential game changer that should be studied for Snowmass**
      - *One caveat is tracklets formed in OT, so will not help with shortest lifetimes … maybe "appearing tracks"?*
  - *AFAIK ATLAS baseline does have triggering at L1, but upgrade with regional tracking at L1 under consideration so could also benefit from studies*
  - *Not all impacts are positive*
    - **CMS will have ~binary readout so less dE/dx discriminant for HSCPs less effective**
      - *Fairly well-studied already*



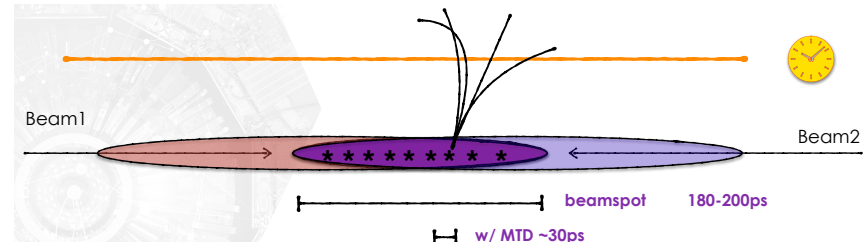
Some good work already done here by Y. Gershtein, S. Knapen arXiv:1907.00007

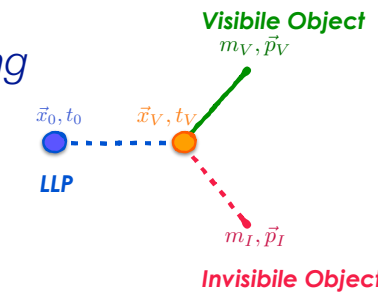


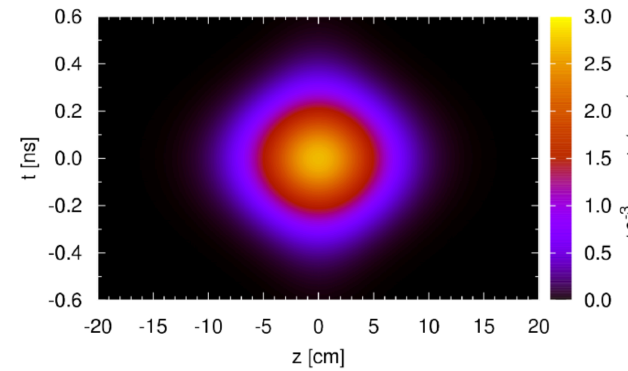


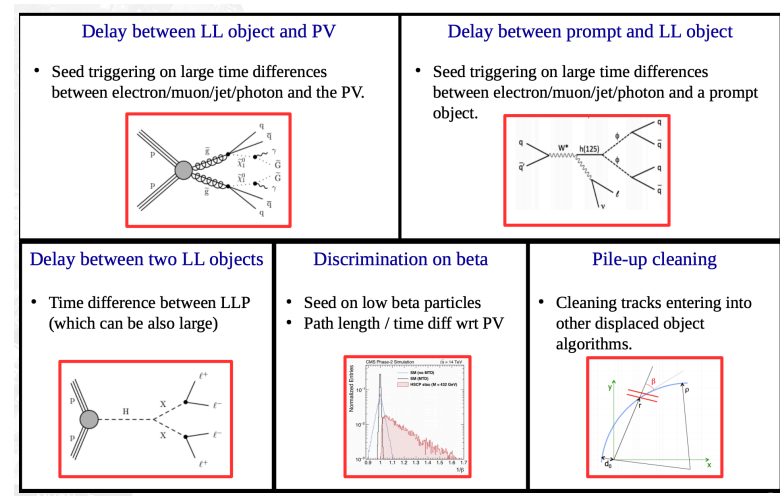
Effect of HL-LHC Timing Upgrades on LLP programs

- *Both CMS/ATLAS* will have timing detectors for the first time for HL-LHC
  - *Unprecedented timing precision of ~30 ps*
  - *Timing is already employed in LLP searches (HSCP, displaced photons, displaced jets) so will obviously help*
  - *Also important to preserve viability of existing program in presence of PU (e.g. searches relying on ISR triggers)*
  - *Enables LLP mass reconstruction with discriminating precision*
  - *I personally do not think it is too late to make case for timing in the trigger (at L1 in CMS)*
    - **Upgrades are always late, and you can always upgrade an upgrade**
    - **Yes, its not in the baseline — so what?**
    - **Potential impact here is hard to overstate**
  - *Snowmass perfect forum to move the ball along here*





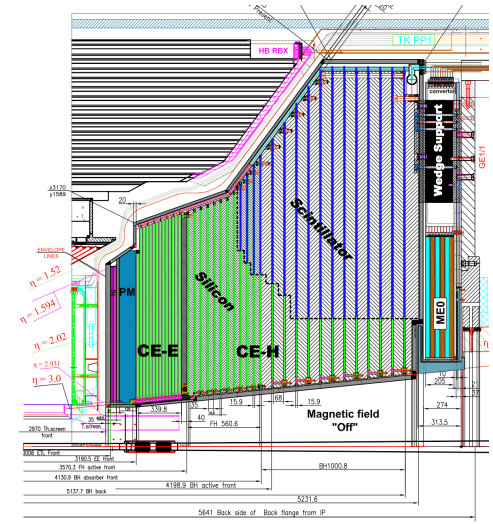


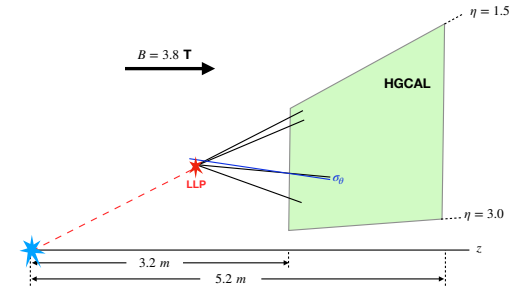


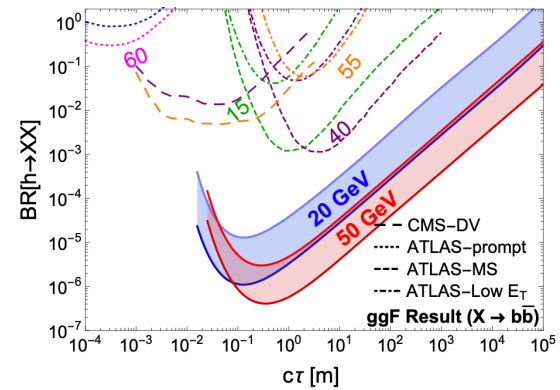
*ATLAS limited to forward region only

Effect of HL-LHC Calorimeter Upgrades on LLP

- Here, I focus on CMS where the entire HCAL will be replaced with a “high granularity” Si imaging calorimeter (HGCAL)
  - *First of its kind, will provide more information about hadronic showers than ever before*
    - **Tracking, calorimetry, timing, all in one!**
    - **Large, expensive, project — focus to date has (correctly) been on securing funding, engineering**
  - *HL-LHC potential for LLP not well explored (AFAIK, save some nice work by theory colleagues, see right)*
    - **Opportunity again for Snowmass to make impact**
  - *How can use all this information to search for LLP?*
    - **Find displaced vertex inside HGCAL (using tracking)?**
    - **Reconstruct mass of decays to neutrals inside HCAL (using timing)?**
    - **Non-SM jets using multiplicity, dE/dx, shower 3D shapes**
      - *Very exotic stuff (e.g. lepton jets monopoles, SUEP, …)*
- I really think, at least for CMS (ATLAS is already doing some of these things) there is a need for good ideas, followed by good studies here



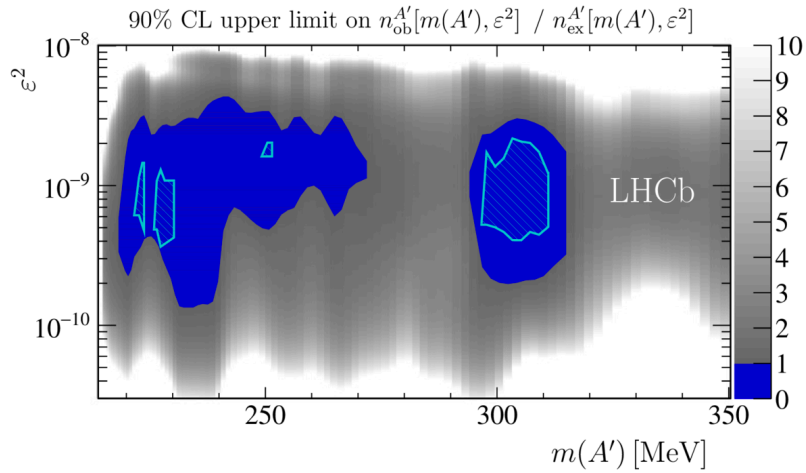




J. Liu et al
arXiv:2005.10836

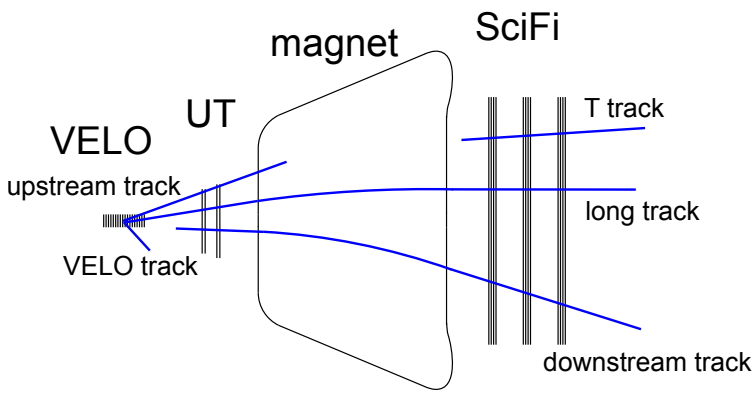
The role of LHCb in LLP searches

- I confess to not having thought much about this topic, but include it here for completeness
  - *Because B's are LLPs, well-suited for (low mass) exotic LLP searches*
    - **Current program includes an LLP search component (e.g. dark photons)**
- For LHCb, HL era starts soon (Run 3)
  - *Plan is to use "Turbo paradigm"*
    - **Do physics analysis on trigger output directly (30 MHz)**



Opportunity* for Snowmass studies on how to exploit this capability for LLPs, also overlap with CMS/ATLAS programs

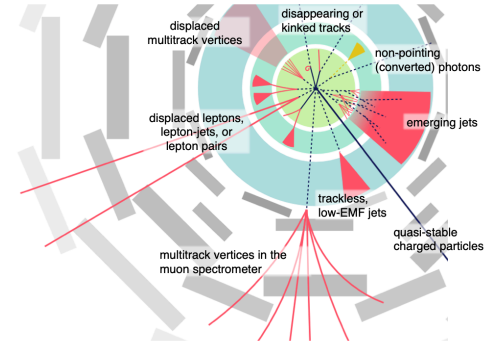
**not much time before Run 3 …*

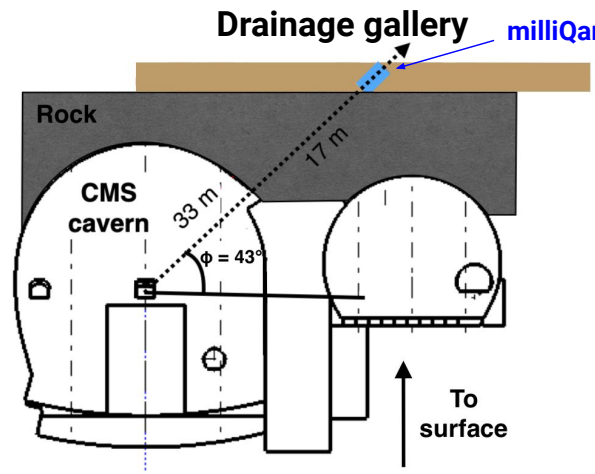


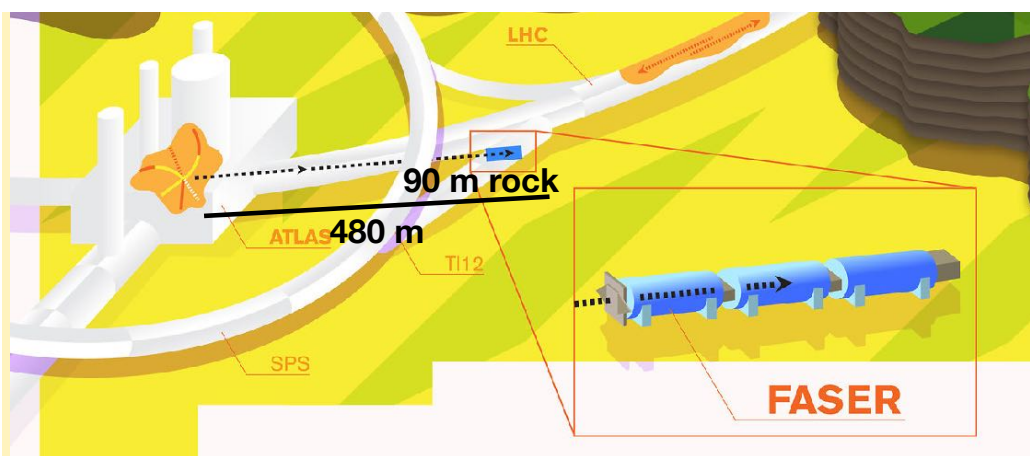
- Core programme: 1- and 2-track selections
- Cut [hard] on one or more of p_T, displacement, e/μ ID, vertex quantities
- VELO geometry restricts LLP vertices to $\mathcal{O}(1\,\text{cm})$ radial and $\mathcal{O}(10\,\text{cm})$ longitudinal displacement from beam spot

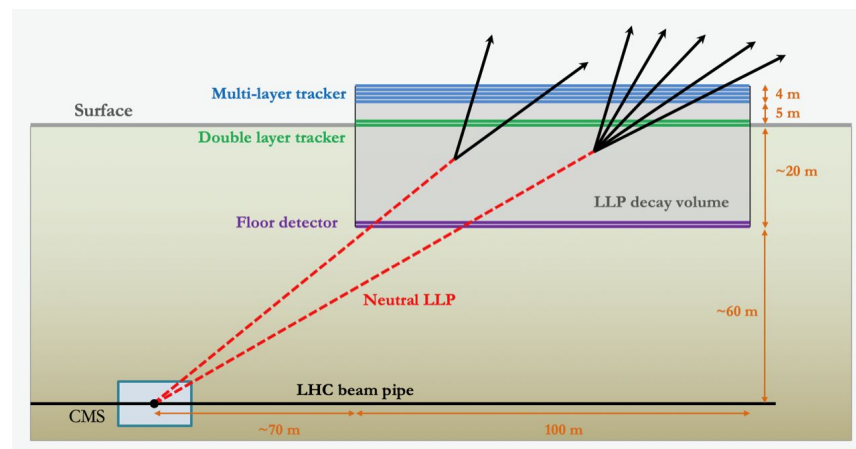
New LHC Experiments

- There will also be (at least one) new LHC experiments during the HL-LHC era (e.g)
  - *FASER (downstream of ATLAS)*
    - **Funded, under construction**
  - *milliQan (off CMS beam line)*
  - *MATHUSLA (on surface above CMS)*
- These experiments "pick up" the LHC LLP search program beyond the radii of ATLAS/CMS
  - *Remember, lifetimes are exponentially distributed*
    - **Just like prompt searches overlap with LLP searches at the short lifetime, the ATLAS/CMS LLP programs overlap with these new experiments**
      - *Have been looked at some by the new exp. proponents*
    - **But, in some/all cases these experiments could be used to trigger ATLAS/CMS**
      - *This has not been studied nearly enough IMHO and is a good candidate for Snowmass*



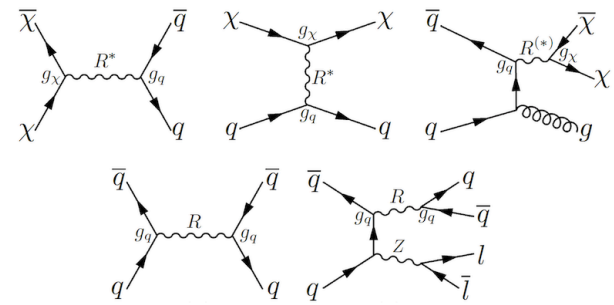


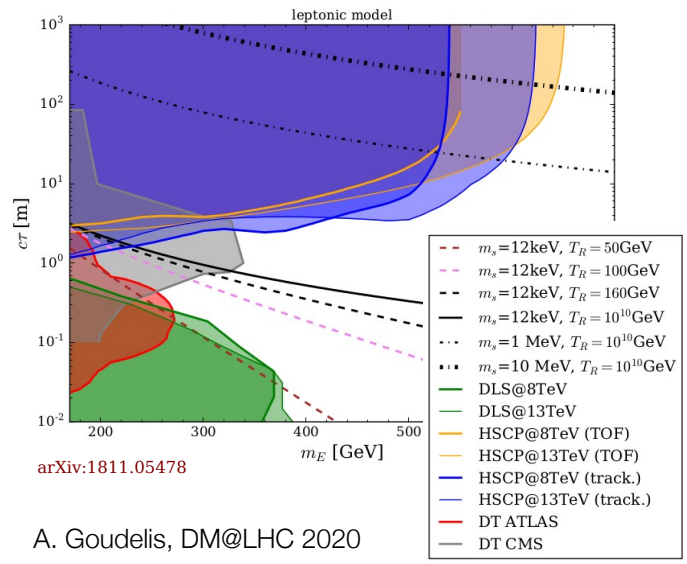




Overlap with DM (Snowmass EF10)? CF? IF?

- There is an obvious synergy between LLPs at LHC and dark matter candidates and/or dark sectors
  - *What makes these "dark" is some kind of suppression of interaction with SM*
  - *If you produce DM from SM collisions at LHC, same suppression of decays back to SM result in long lifetimes*
- Despite being on the APS/DPF committee that helped to set up this Snowmass, I am not really sure how to handle such overlaps
  - *But clearly work on LLPs EF9 should be made aware/ available to EF10 somehow*
    - **From EF10 side, I think C. Daglioni is the point of contact?**
  - *There is also a similar (but maybe worse) issue with the overlap with the cosmic and intensity frontiers*
- I have no real suggestions here, just raising the point for possible discussion





A. Goudelis, DM@LHC 2020

Connection between the relic abundance with the parent particle lifetime:

$$c\tau \approx 4.5\,\mathrm{m}\,\xi g_F \left(\frac{0.12}{\Omega_s h^2}\right)\left(\frac{m_s}{100\mathrm{keV}}\right)\left(\frac{200\mathrm{GeV}}{m_F}\right)^2\left(\frac{102}{g_*(m_F/3)}\right)^{3/2}\left[\frac{\int_{m_F/T_R}^{m_F/T_0} dx\, x^3 K_1(x)}{3\pi/2}\right]$$

Can constrain cosmologically relevant parameter space.

Summary

- The LHC experimental LLP program has grown in the last few years
  - *Many more "ideas" than published papers, however.*
  - *This is because good LLP searches are hard (due to often unique experimental challenges)*
  - *In my view the best ones expand the capabilities of our detectors in ways they weren't designed to work (but within the constraint of reasonable feasibility)*
- The significant new information that the upgraded HL-LHC detectors will provide should be a great source of inspiration for LLP hunters
  - *Continue pushing the boundaries of LLP searches*
  - *Snowmass is a unique opportunity to explore ideas that are beyond-the-baseline and for which there might not be bandwidth to pursue under official ATLAS/CMS/US projects*
    - **No P6 task entitled "come up with good idea to revolutionize LLP searches in the next decade"**
  - *Especially important to use this time to try to fully exploit new trigger ideas (using L1 tracks, MTDs, or auxiliary experiments)*
    - **BTW, I'm happy to work with people on any of the above (esp. the last one)**

That’s my 2 cents. I hope I left time for discussion of next steps …

Additional Material

ATLAS LLP Summary Plot (cf. CMS slide 2)

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