Searches for long-lived particles at the LHC

ATLAS & CMS have published numerous searches for long-lived, exotic particles.

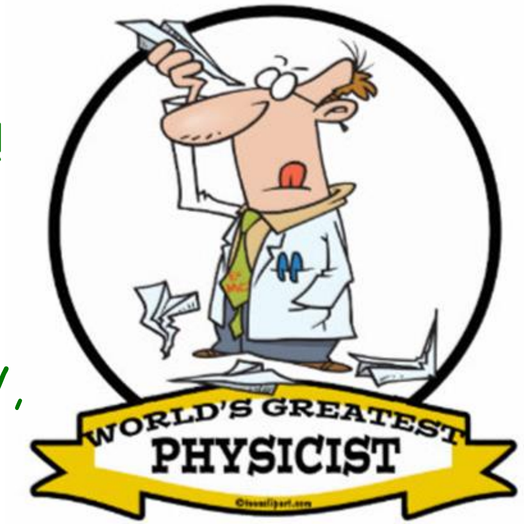
- What motivates these searches ?
- What strengths & weaknesses do the two detectors have for such searches?
- I will present analyses illustrating the main techniques and ask:
  - How well are we exploring the phase space ?
  - How are we doing with *model-independent* results?

Motivation

- Theoretical physicists are *brilliant* at inventing models with long-lived (LL) particles !

  There are loads of them:

  - e.g. In RPV SUSY, AMSB SUSY, GMSB SUSY, Hidden Valley models …



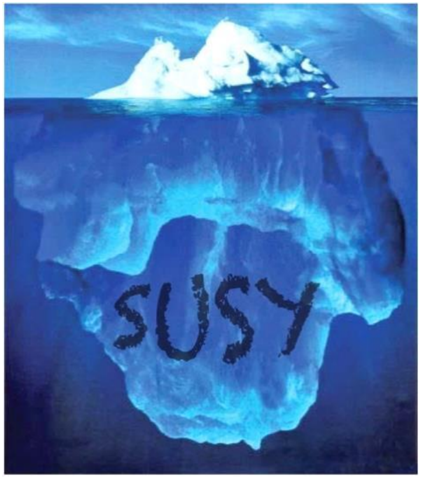
- **Lessons:**
  - LL exotica are well worth looking for.
  - Experimental searches should use simple signatures that are each sensitive to many LL models.
  - Present limits in model-independent way !

Motivation

- Long-lived signatures can hide new physics, such as SUSY, from conventional ATLAS & CMS searches.

  e.g. In the case of SUSY:

  - If LSP decays to visible particles before calorimeter, then E_T^{miss} signature used by classic SUSY searches will disappear.
  - What about dedicated RPV SUSY searches? These assume the LSP decays *promptly*, so fail if the LSP decay length exceeds a few mm.

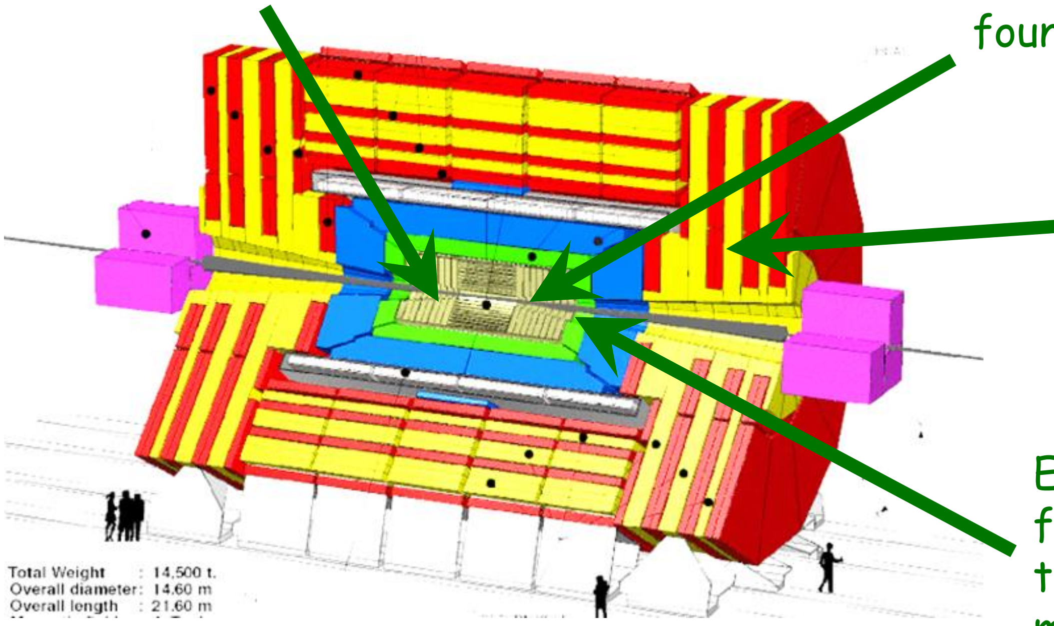


Searching for Long-Lived Particles illustrated with the CMS detector

Tracker can reconstruct charged particles from LL particle decay up to 50 cm from LHC beam-line.

Heavy, charged particles traversing Tracker can be found via dE/dx measurement.

They are also identified in μ-chambers via time-of-flight (TOF) measurement.



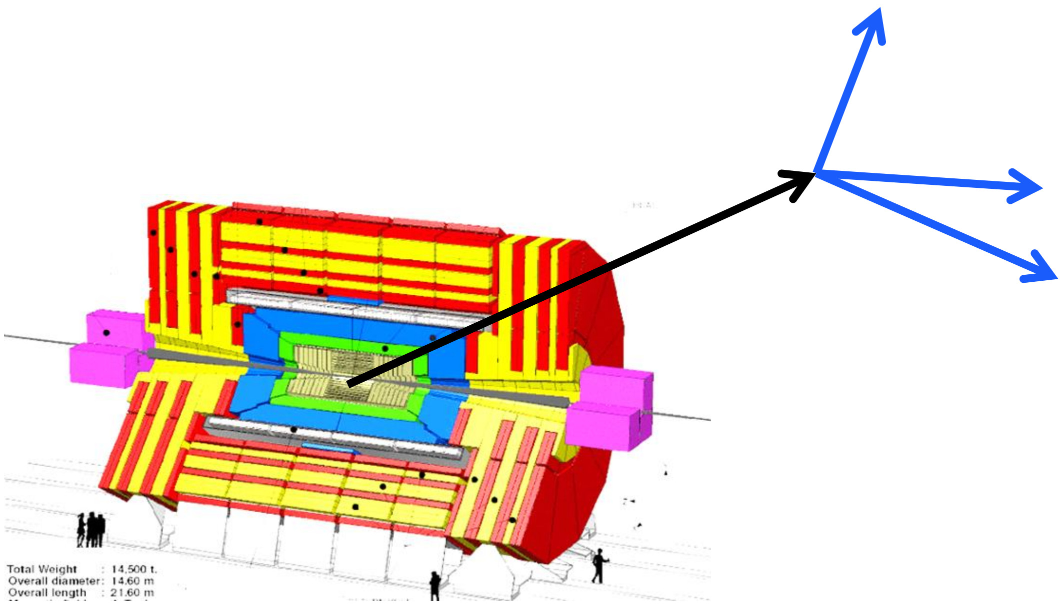
ECAL can find photons from LL particle decay via time-of-flight (TOF) measurement.

ATLAS better at some things:

- Their ECAL is great at finding photons from LL particle decay, as it measures photon *direction*.
- Their muon chambers are surrounded by *air*, not *iron*, so they can track hadrons from LL particle decay inside them, in addition to muons.

Very Long-Lived Charged Particles

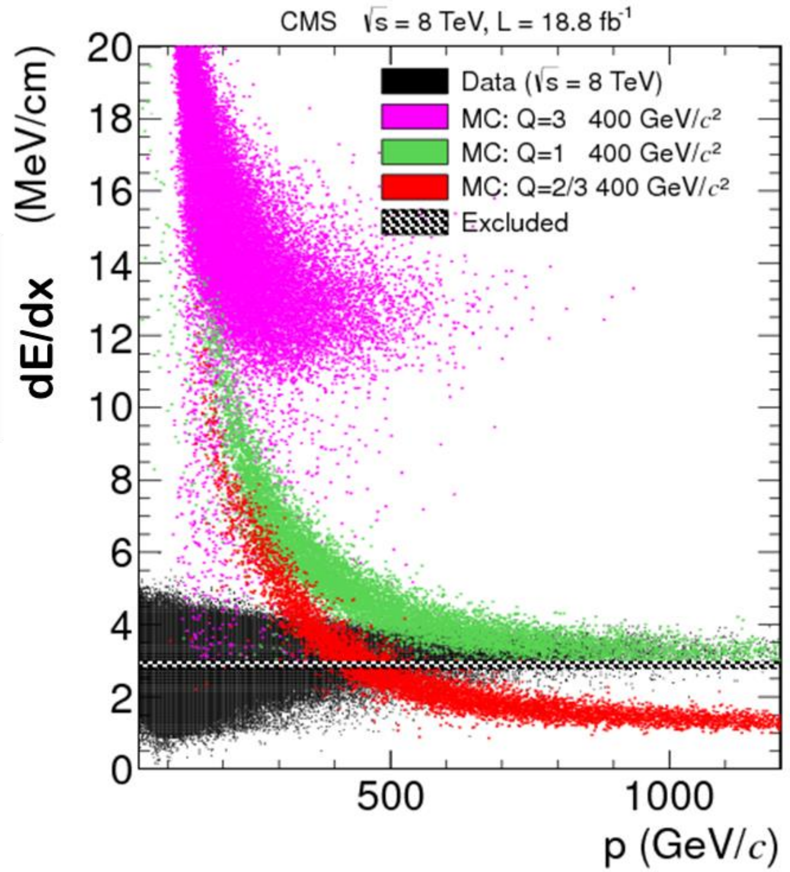
(i.e., which traverse detector before decaying)



CMS search for heavy stable charged particles (HSCP) (CMS-PAS-EXO-16-036)

CMS analysis with 13/fb of 13 TeV 2016 data.

- HSCP are massive & slow moving.
- There are 3 key selection variables:
  1. Track Pt
  2. dE/dx from Tracker
  3. TOF from μ chambers
- These 3 variables are statistically uncorrelated for SM particles, which allows the background to be estimated from the data.
  - e.g. dE/dx has little dependence on Pt for relativistic particles.



CMS search for heavy stable charged particles
Different search strategies for different particles!

- Search for long-lived $\tilde{g}$, $\tilde{t}$ and $\tilde{\tau}$.
  Coloured particles ($\tilde{g}$, $\tilde{t}$) hadronize into R-hadrons with SM q/g.

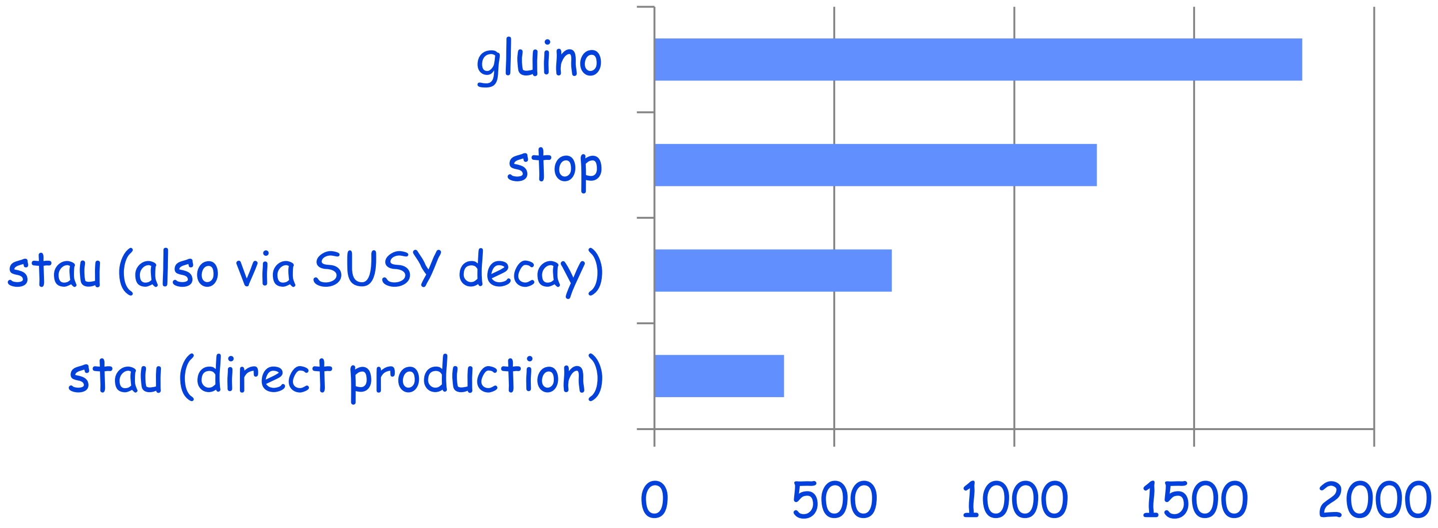
- R-hadrons flip charge as they pass through the CMS detector material.
  A charged R-hadron may be neutral when it reaches the outer detector!

- Unsure how often $\tilde{g}$ forms neutral hadron with g. Could be 100%!
  If so, track would start neutral (invisible) but may become charged through interaction with detector.

- Therefore do searches using:
  - "tracker + muon chambers" (for $\tilde{\tau}$)
  - "tracker only" (for initially charged R-hadron: $\tilde{t}$, $\tilde{g}$)
  - "muon chambers only" (for initially neutral R-hadron: $\tilde{g}$)

CMS search for heavy stable charged particles
Results

- 95% CL lower mass limits obtained:



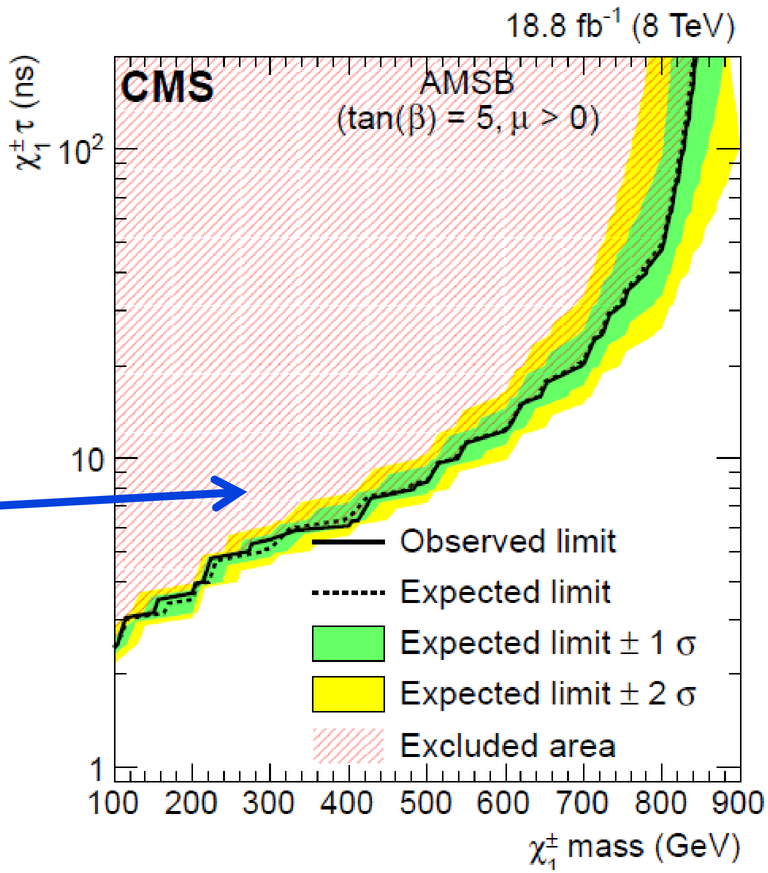
- N.B. Limits on $\tilde{g}$ & $\tilde{t}$ vary by ~100 GeV, depending on R-hadron assumptions.

CMS search for HSCP (CMS/2015 arXiv:1502.02522)
Towards model independent results …

- Publish number of data candidates passing cuts & the expected background.
- Publish selection efficiency vs. Pt, β & η of HSCP.
- If HSCP lifetime is small, multiply this by prob that it transverses CMS before decaying: $\exp[-M\, L(\eta) / c\, \tau\, P]$.

- Can now estimate efficiency & hence limits for arbitrary HSCP model, if kinematics known at generator-level.

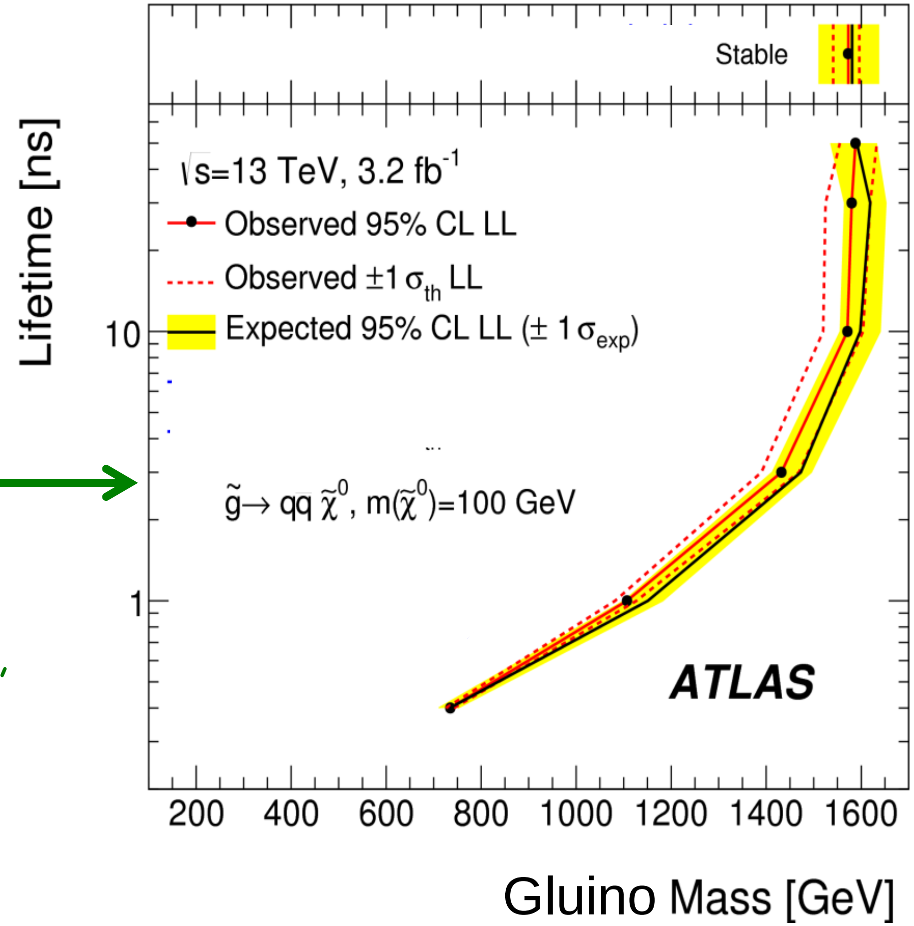
- For example …
  - In AMSB, $\tilde{\chi}^+ \to \tilde{\chi}^0 \pi^+$, where $\tilde{\chi}^+$ is long-lived, get limits extending down to χ^+ lifetimes of ~2 ns.



ATLAS search for heavy stable charged particles (HSCP) (arXiv:1604.04520+1606.05129)

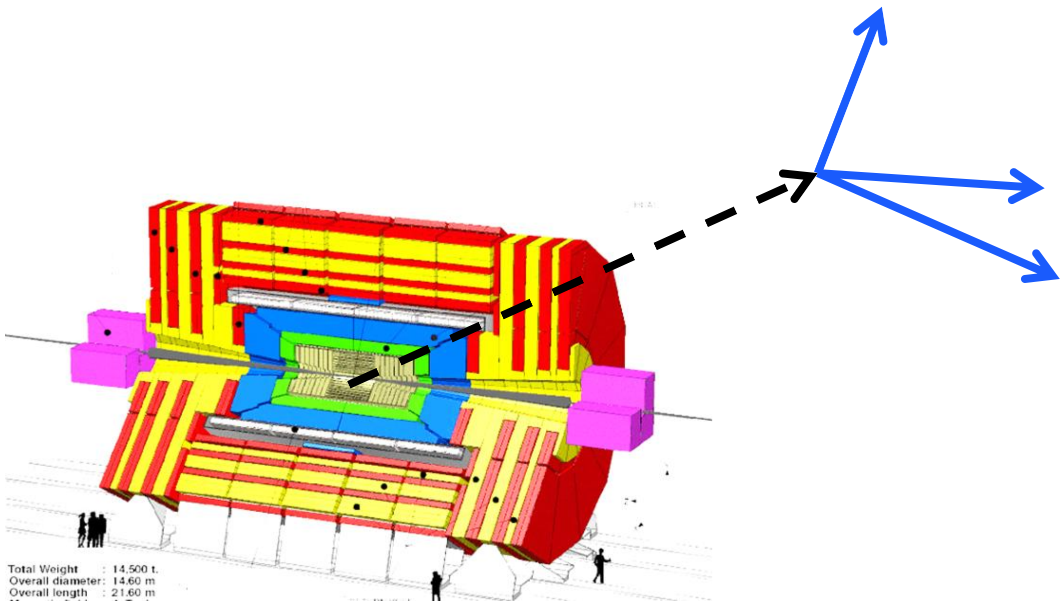
Based on 3/fb of 13 TeV 2015 data.

- Similar technique to CMS, but using dE/dx in pixel tracker + optionally TOF from HCAL.
- Nice feature: quote limits as a function of gluino lifetime, in addition to its mass.
  - ➢ Limits weaken at small lifetime, as probability gluino traverses tracker is lower.



Very Long-Lived Neutral Particles?

(i.e., which traverse detector before decaying)



Only detectable via E_t^{miss} signatures.

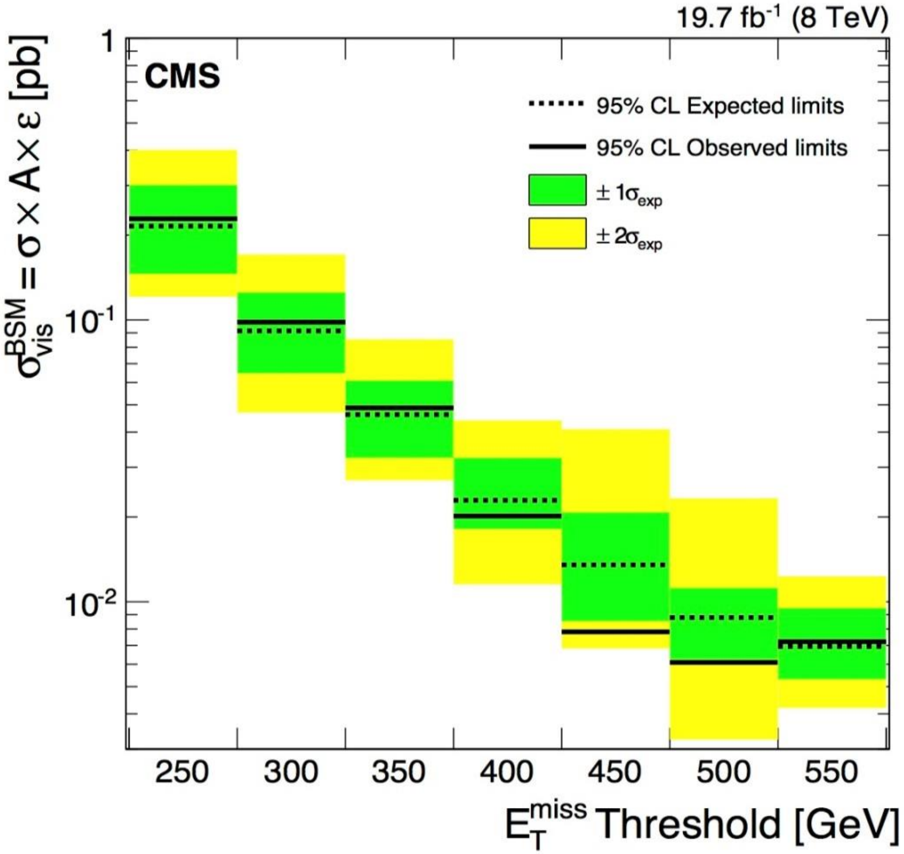
Detecting long-lived, neutral particles via E_T^{miss} searches.
An example …

- Jet+MET searches provide limits on long-lived, neutral particles that decay outside the detector & so are invisible.

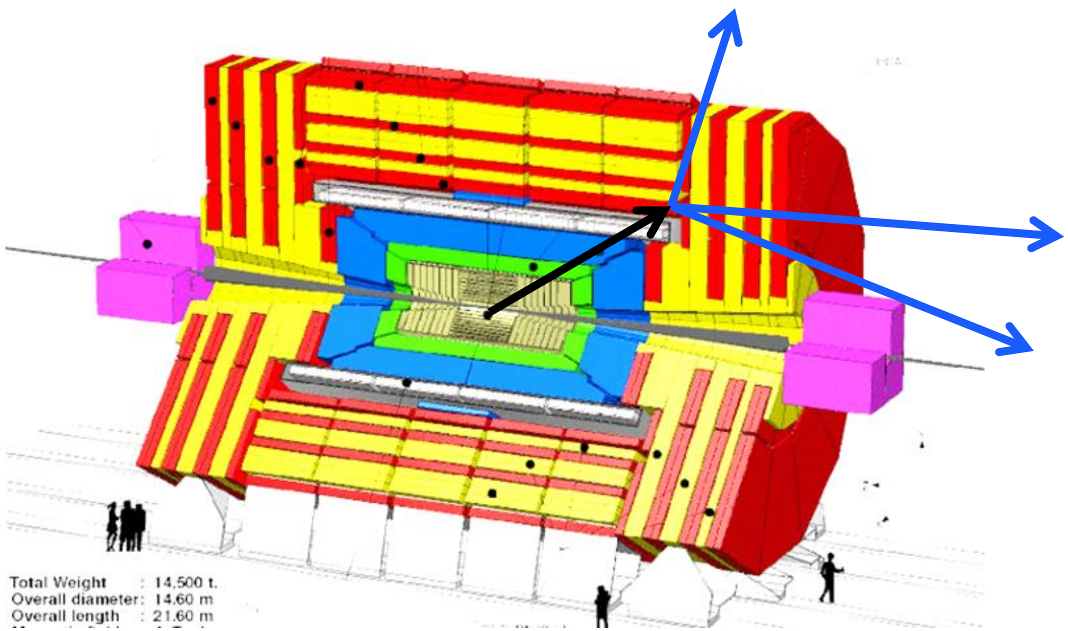
- e.g. The CMS monojet search (arXiv:1408.3583) limits pair production of dark matter particles accompanied by ISR jet.
  - The same limits apply to LL neutral particles that decay outside CMS ($R \gtrsim 10$ m).

- Belyaev *et al* extend this method to put limits on LL signals vs. lifetime. (arXiv::1512.02229)

Model-independent monojet limits



Long-Lived Particles that decay within the detector volume



Look for leptons, jets or photons that do not originate at the pp collision point.

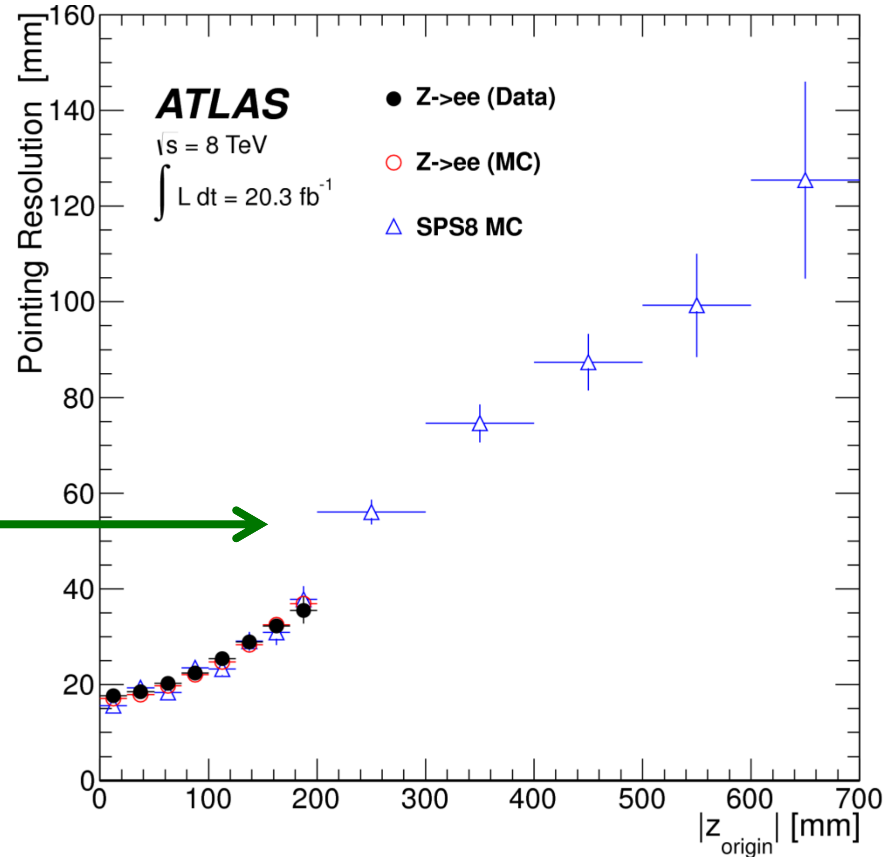
Search for long-lived particles decaying to displaced photons ATLAS/2014 (arXiv:1409.5542)

- In GMSB SUSY: long-lived $\tilde{\chi}^0 \rightarrow \gamma\, \tilde{G}$.
- Expect 2 $\tilde{\chi}^0$ per event, so trigger requires 2 photons.
- Offline, also require missing Et from $\tilde{G}$.

- Profit from depth-segmented ECAL, to measure photon flight direction!
  - Hence estimate z_0 impact parameter of photon.
  - z_0 should be small for background & large for signal.

- Z→e+e- used both to measure **z_0 resolution**

  & prompt γ background shape in z_0.

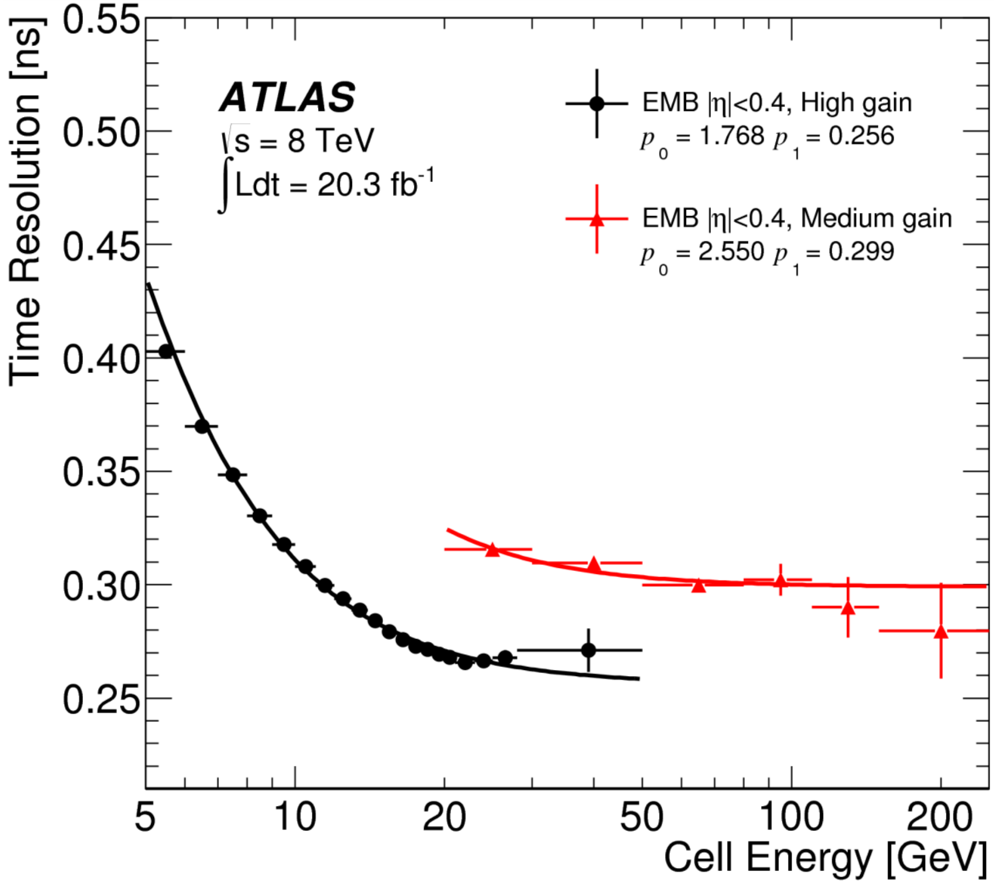


Search for long-lived particles decaying to displaced photons ATLAS/2014

- ATLAS can also measure TOF of photon in ECAL.
  - TOF should be smaller for photons from background than those from signal.

- Z→e+e- used to measure **TOF resolution** →

  & prompt γ background shape in TOF

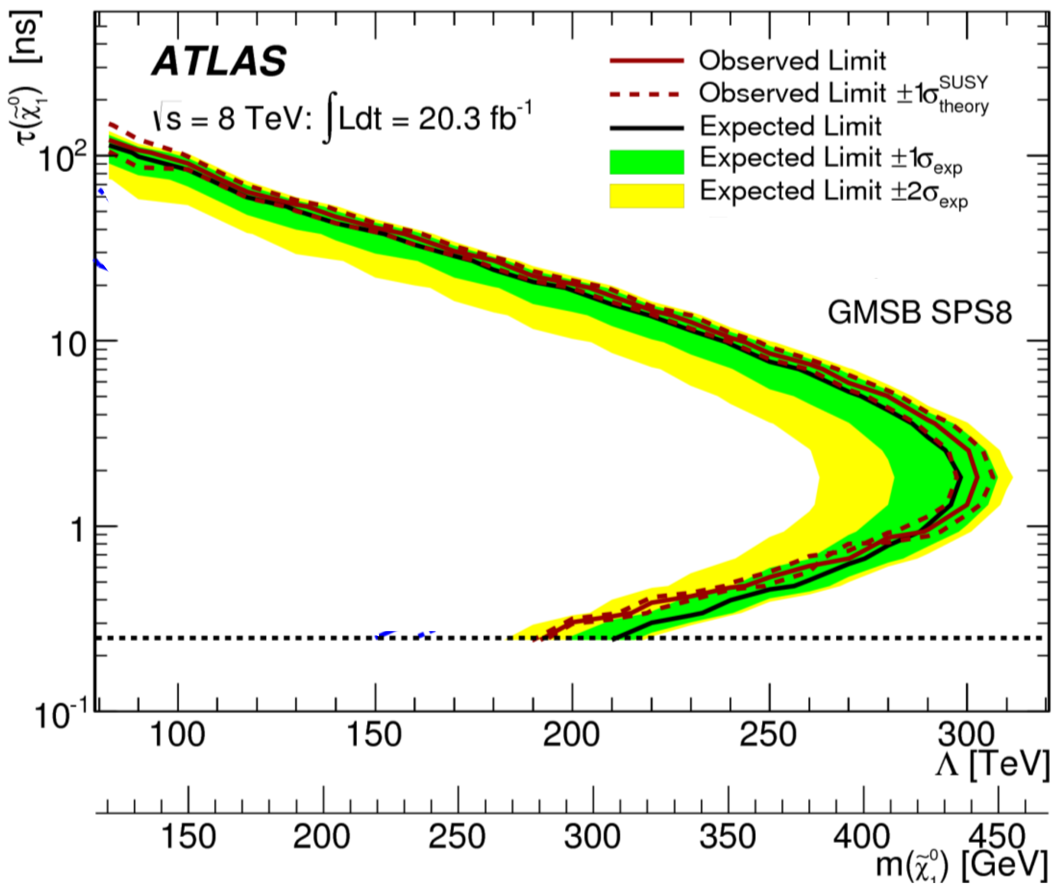


Search for long-lived particles decaying to displaced photons (ATLAS/2014)

- Fit to photon z_0 impact parameter & TOF distributions to get limits in plane of $\tilde{\chi}^0$ lifetime vs. mass, assuming SPS8 SUSY parameters.
- Limits based on 20/fb of 8 TeV 2012 data.

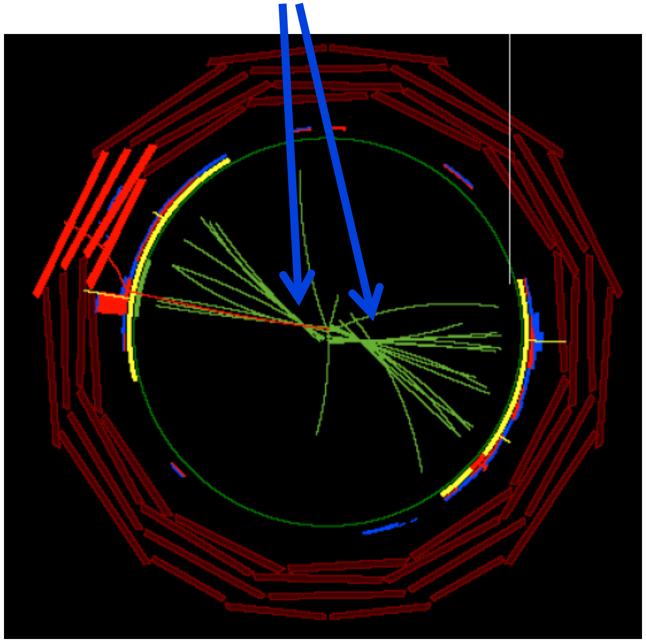
- N.B. Selection is sensitive to *any model* giving displaced photons!
  - ➢ So presenting limits in a more model-independent way would be welcome …

- CMS has a less competitive analysis. (CMS-PAS-EXO-12-035).



CMS search for LL particles decaying to displaced jets in tracker (CMS/2014 - arXiv:1411.6530)

- CMS searches with *19/fb of 8 TeV 2012 data* for LL particle decays to $(q, \bar{q}, \text{anything})$.
  - Look for 2 jets whose associated tracks form a single *displaced vertex* in Tracker.



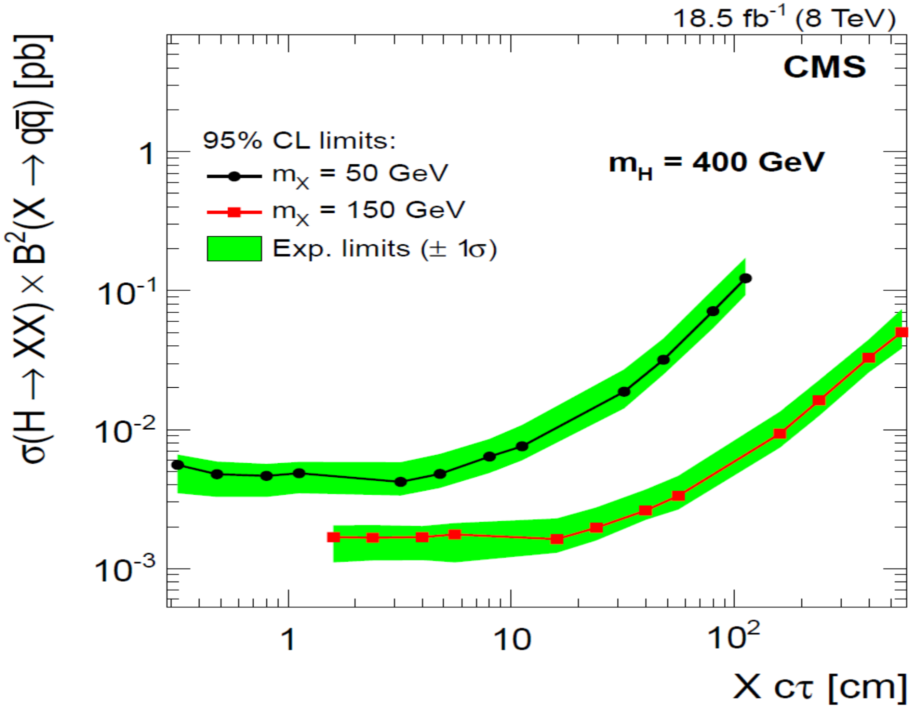
- Example of signal models considered: Higgs → 2X → $(q\bar{q})(q\bar{q})$,

- Main difficulty is **triggering** on these events.
  - Required 2 jets of Et > 60 GeV *with few associated prompt tracks.*
  - Also required HT > 300 GeV (total transverse energy in event) Makes analysis *insensitive* to 125 GeV Higgs decays!

  - Threshold could be reduced in future by triggering on other particles produced in association with LL particle. (But increases model-dependence).

CMS search for long-lived particles decaying to displaced jets in tracker

- Only 2 events passed selection, consistent with expectation, so quote limits.



- Found no (simple) model-independent way of presenting limits.

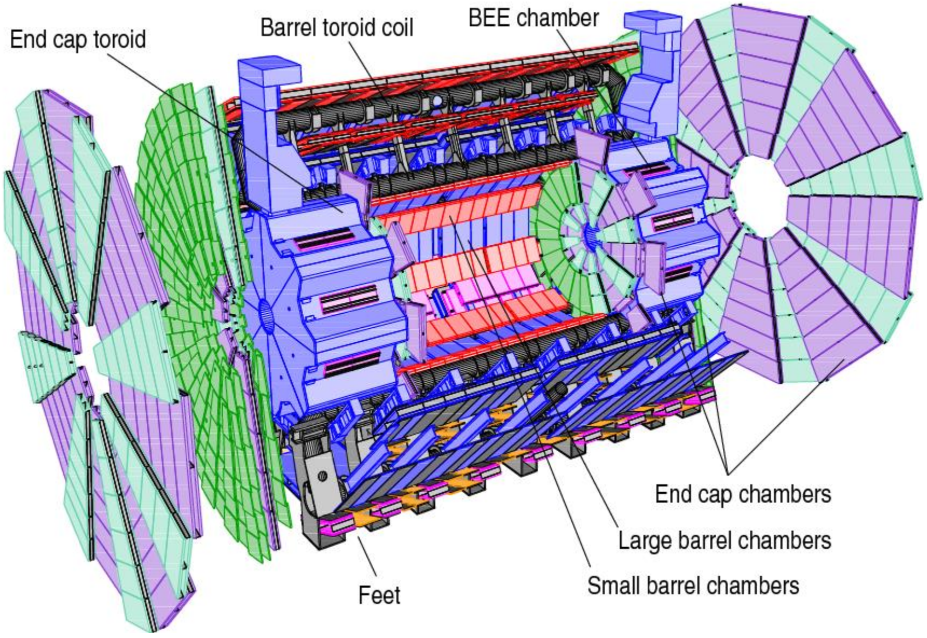
ATLAS search for LL particles decaying to displaced jets in muon spectrometer (ATLAS/2015 - arXiv:1504.03634)

- ATLAS searches for similar Higgs → 2X → $(q\bar{q})(q\bar{q})$ signal to CMS, but looking for X boson decays inside muon spectrometer.

- Muon spectrometer lies at 4 < r < 10 metres from beam-line. Sensitive layers are separated by *air*, (unlike CMS, which uses steel), so hadrons from X decay fly far enough to be reconstructed.

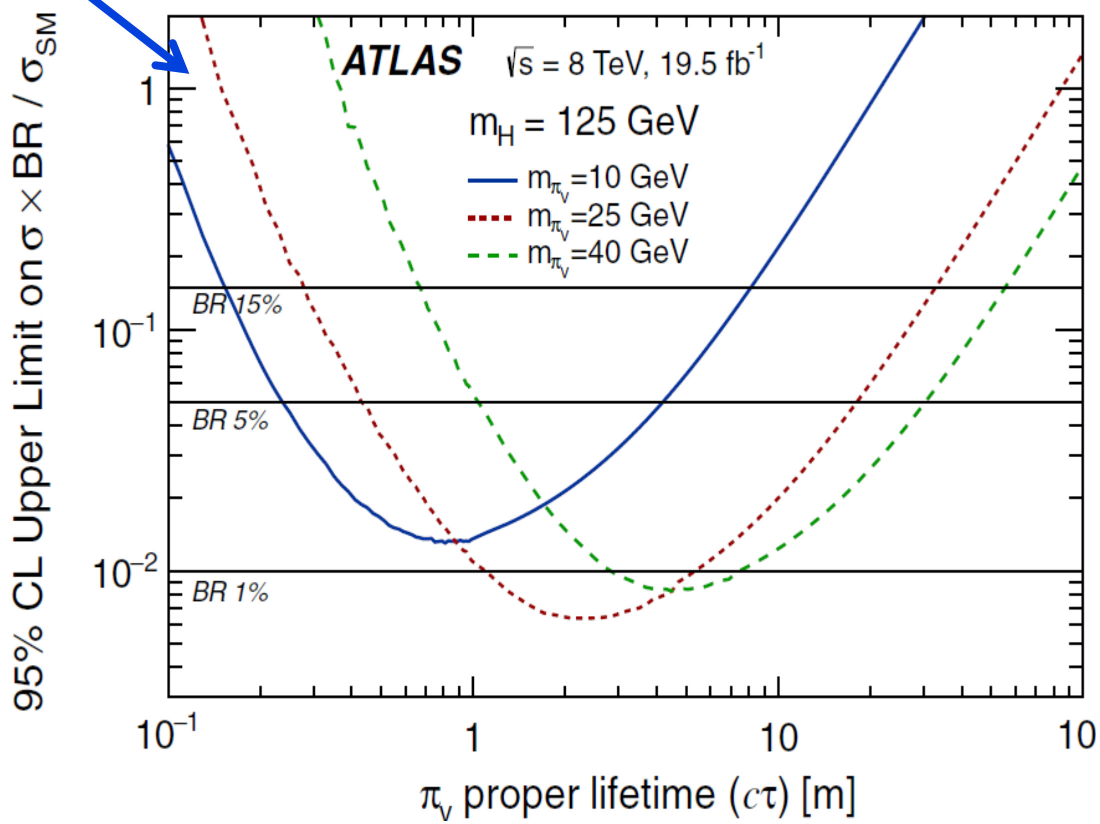
- Trigger looks for these unusual jets of particles in muon spectrometer.
  - Has much lower Et threshold than CMS!

- Require 2 reconstructed X decay vertices per event.



ATLAS search for LL particles decaying to displaced jets in muon spectrometer

- No events found.
- Thanks to low E_T threshold trigger, can set limits for 125 GeV Higgs: BR of Higgs → 2X → $(q\bar{q})(q\bar{q})$ < 1% for cτ ~ 2 metres.
- N.B. Peak sensitivity at longer decay lengths than CMS Tracker-based search.

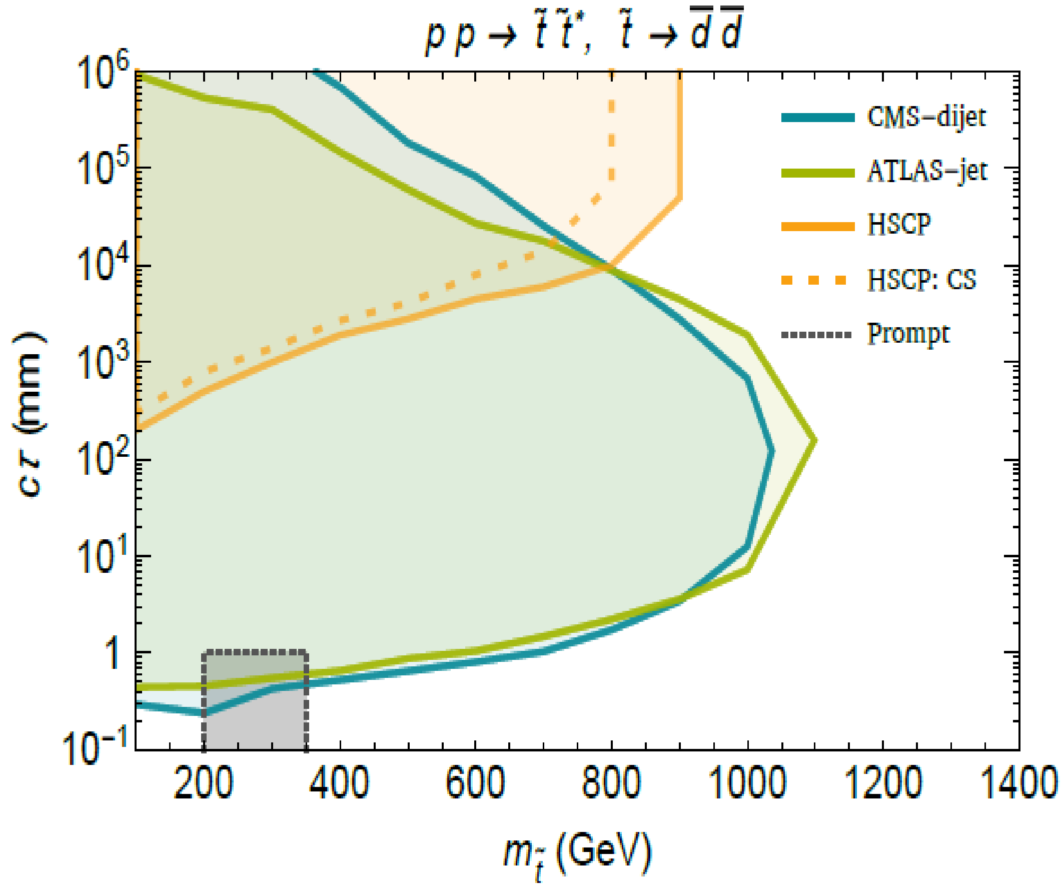


Displaced jet searches reinterpretation by phenomonenologists

- Although CMS & ATLAS don't present displaced jets results in model-independent way, the powerful limits tempted phenomenologists to reinterpret them!

- Very interesting results by Tweedie (arXiv:1503.05923) & Csaki (arXiv: 1505.00784) *et al.*

- e.g. For long-lived top squarks (LSP) decaying via RPV to diquarks, get limits from:
  - CMS HSCP search for $c\tau$ > 500cm.
  - CMS displaced jet & ATLAS displaced vertex (1504.05162) searches for $c\tau$ < 500cm.



Search for LL particles decaying to displaced leptons (CMS-PAS-EXO-16-022 + ATLAS-CONF-2016-042)

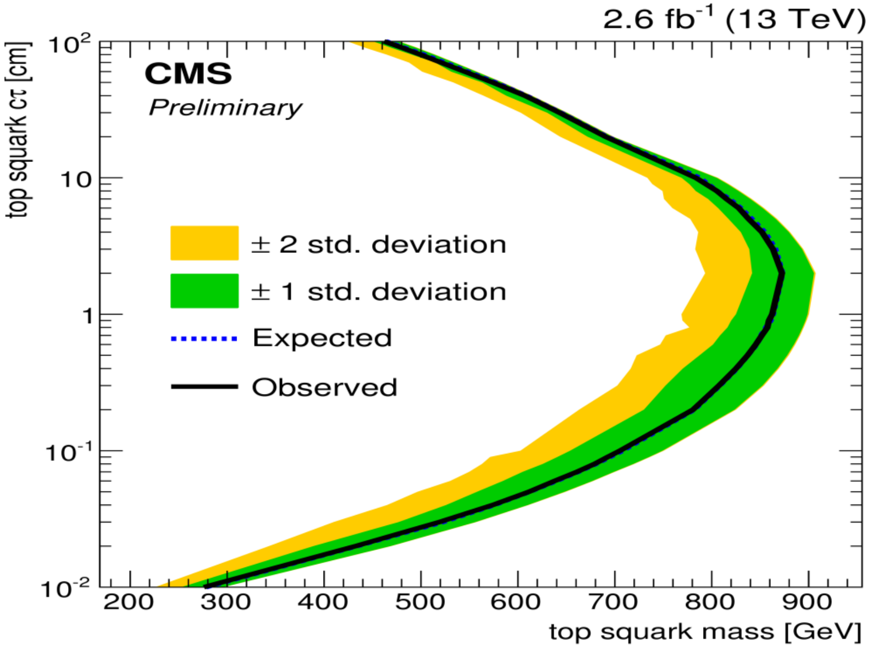
Let's look at 2 papers produced with 3/fb of 13 TeV 2015 data

- ***CMS*** looks for events with one displaced electron + one displaced muon, reconstructed in tracker (short decay lengths).
  - These are ***not*** required to form a common vertex.
    - ***good idea*** since it broadens range of models we are sensitive to.

- Almost no background.
  - Limits placed on LSP top squark decaying via RPV SUSY:

    2*(long-lived $\tilde{t}$)→ (b e)(b μ)

- **Extreme simplicity of selection allows limits to be transferred to many other signal models,** (providing efficiency dependence on decay length etc. published).



Search for LL particles decaying to displaced leptons (CMS-PAS-EXO-16-022 + ATLAS-CONF-2016-042)

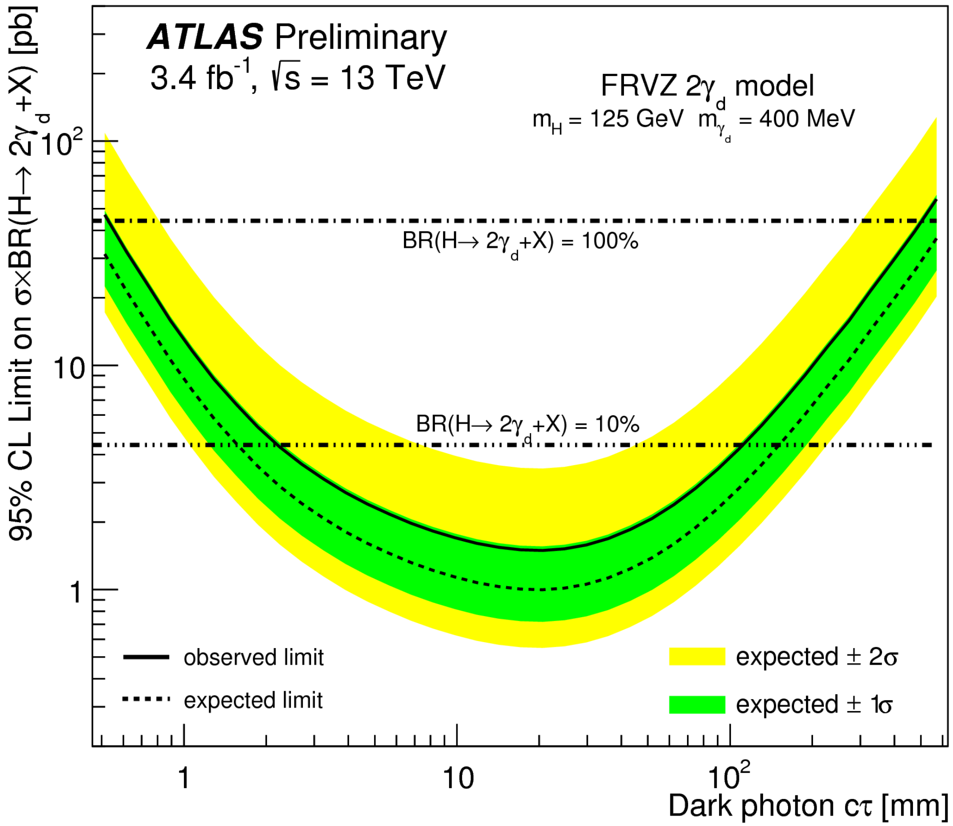
- **ATLAS** looks for pairs of "lepton jets" reconstructed in muon spectrometer or calorimeter (long decay lengths).

  Typical signal model: **H → 2*long-lived → 2(γ_D + invisible) → 2(l^+l^- + invisible)**

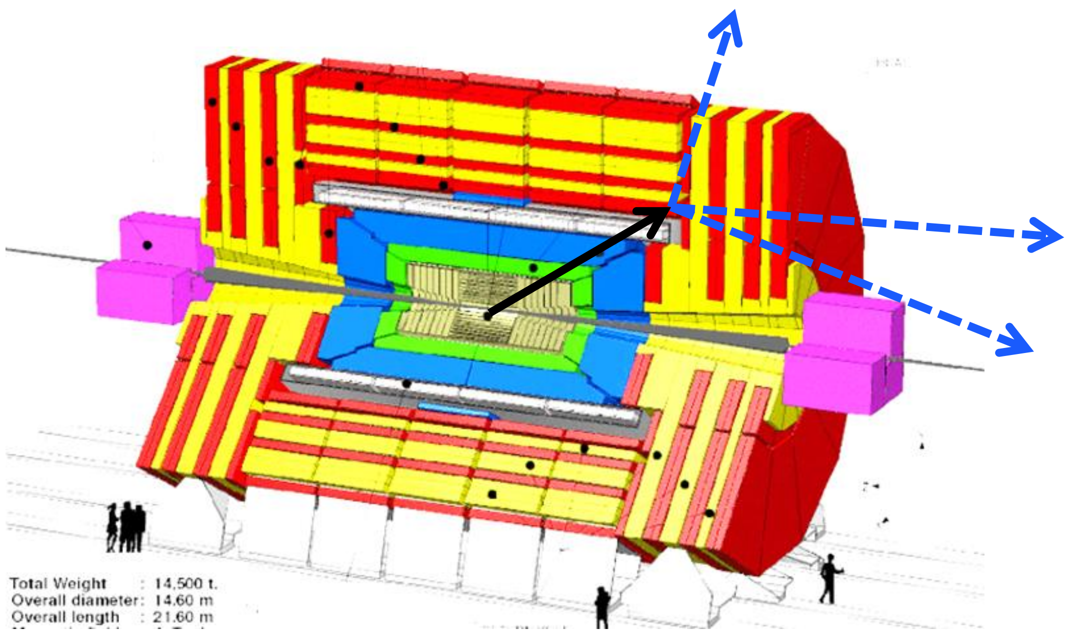
  where γ_D is a very light (M ~ 1 GeV) "dark photon".

- Sets limits on BR of 125 GeV Higgs ~5% for $c\tau$ ~ 1cm.

  (N.B. γ_D have large Lorentz boost)



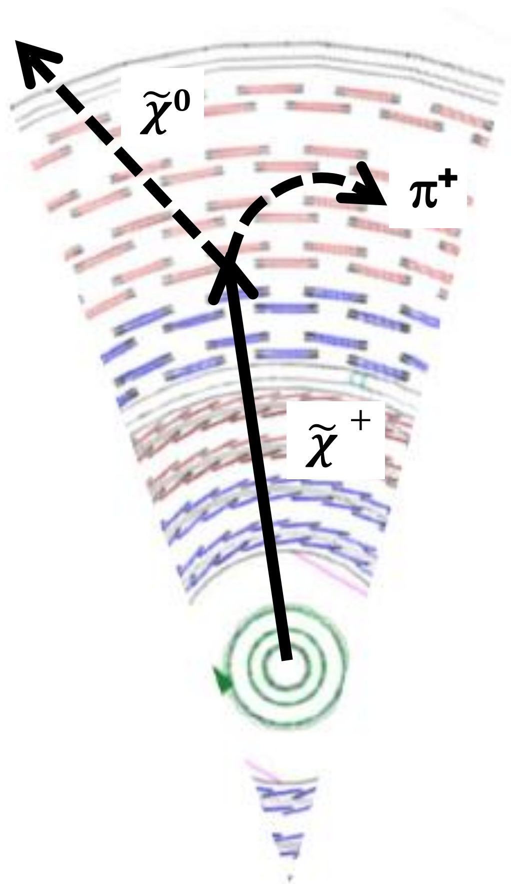
Long-Lived Particles that decay within the detector volume *to invisible particles* (!)



Possible if the long-lived particle is *charged* …

CMS disappearing (HSCP) track search (arXiv:1411.6066)

- In AMSB, $\tilde{\chi}^+ \rightarrow \tilde{\chi}^0 \pi^+$, where the $\tilde{\chi}^+$ and $\tilde{\chi}^0$ are almost mass degenerate. The $\tilde{\chi}^+$ is long-lived. Let us assume it decays somewhere inside the Tracker. The π^+ is very soft & usually undetectable.



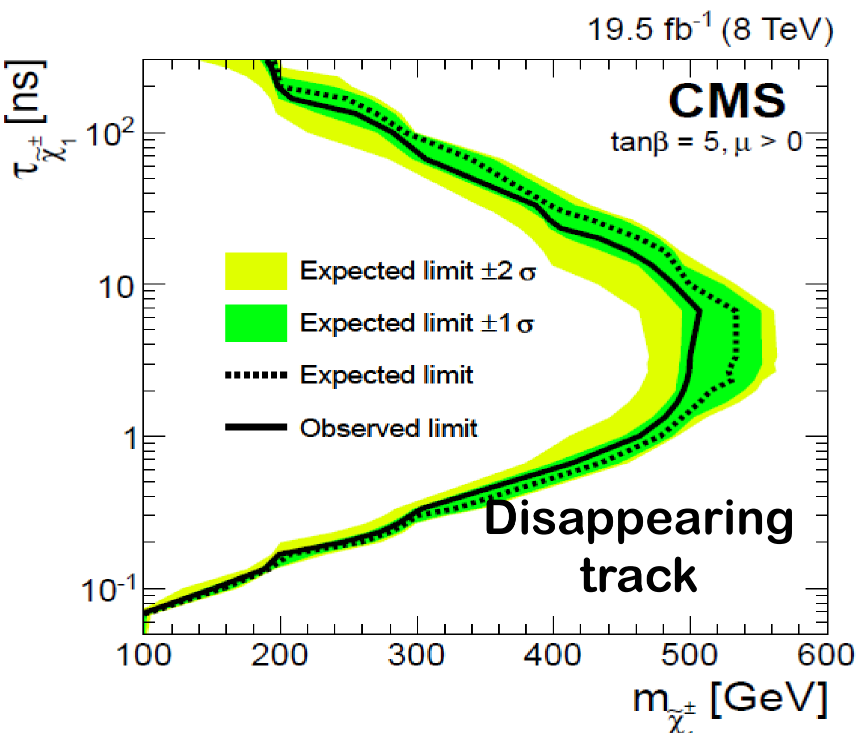
- Trigger using ISR jet + missing Et (from $\tilde{\chi}^0$), since can't trigger on π^+.

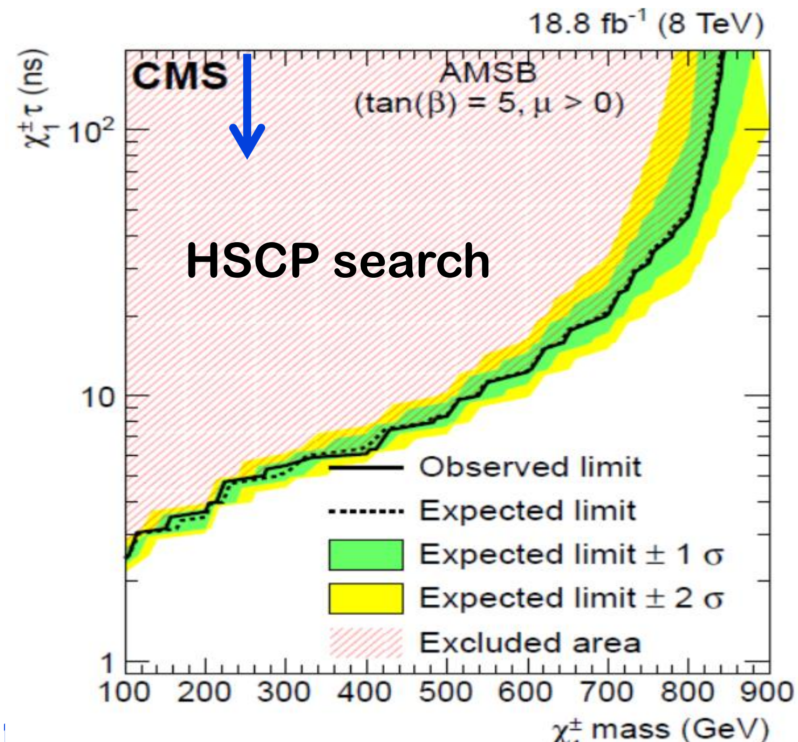
- Offline: $\tilde{\chi}^+$ seen as track with no hits in outer layers of the Tracker.
  But there are *loads* of such tracks, due to nuclear interactions!

- Rescued by additional cuts, e.g. requiring track to:
  - Have Pt > 50 GeV.
  - Be isolated.

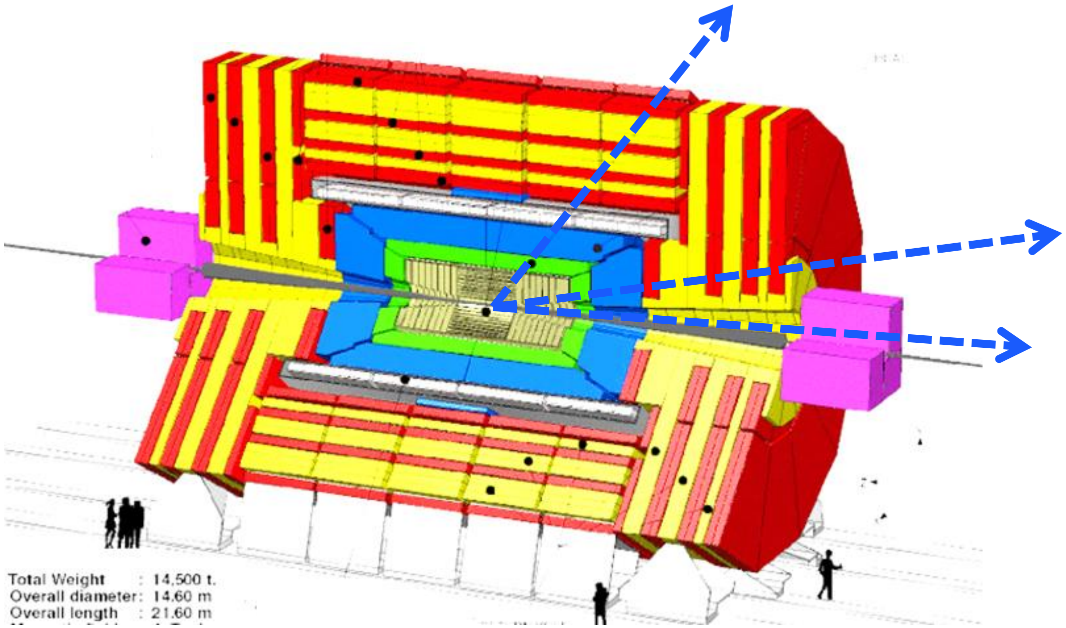
CMS disappearing (HSCP) track search (arXiv:1411.6066)

- After all cuts, only 2 tracks survive.
  - Good limits (although not yet presented in model-independent way …)
- *These* limits extend to lower lifetime *those* from HSCP search (slide 9).





Long-Lived Particles with very short lifetimes



Do conventional searches tell us about LL particles ?

- What about LL particles that are so *short-lived* that they have little chance of decaying to significantly displaced fermions?

  N.B. A priori, it is equally likely that a hypothetical LL particle has 0.01 cm < $c\tau$ < 0.1cm as 10 cm < $c\tau$ < 100cm!

Conventional searches can help answer this questions …

e.g. SUSY searches assume that the LSP is stable & everything else decays instantly. But their limits remain ~valid if the LSP usually decays outside the detector ($R \gtrsim 10$ m) & everything else decays at $R \lesssim 1$ mm.

  - CMS SUSY search for $\tilde{\chi}^{+} \to l^{+} \upsilon\, \tilde{\chi}^{0}$ (arXiv:1405.7570) constrains short-lived $\tilde{\chi}^{+}$ ($R \lesssim 1$ mm)

- Ideally, long-lived exotica signal MC should be run through conventional searches to determine exactly which lifetimes they are sensitive to.


Conclusions

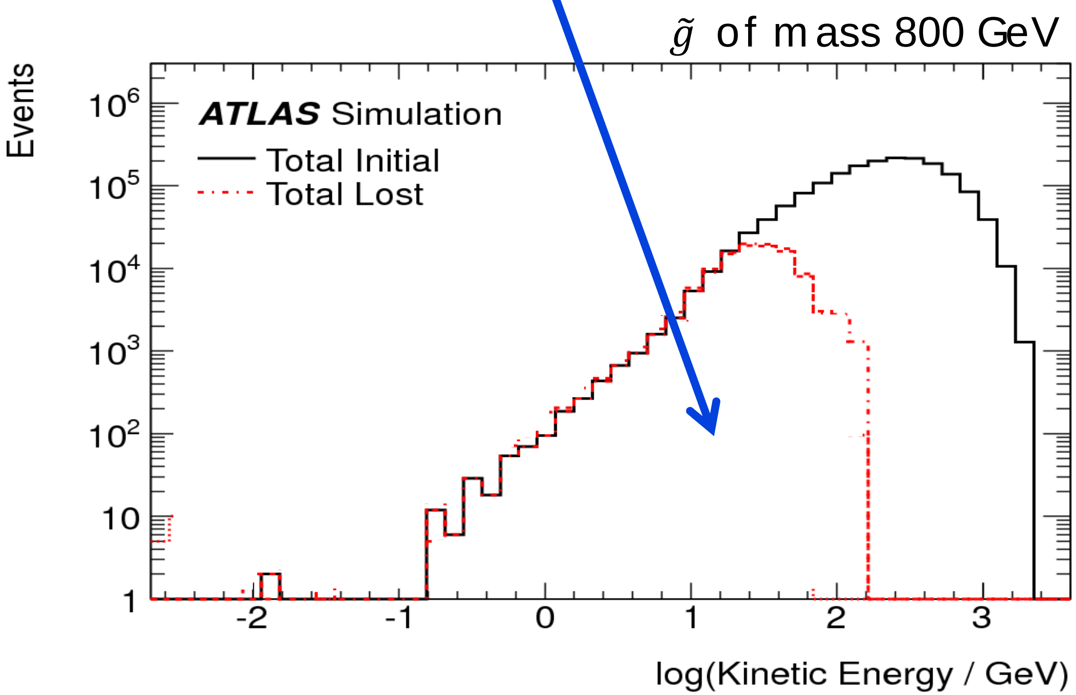
Conclusions

- Searches for LL particles are usually based on simple signatures that are sensitive to a wide range of models.
  - Massive, stable charged particles.
  - Missing transverse energy.
  - Displaced leptons, jets or photons.
- Some of these searches attempt to present limits in a model-independent way, though not always easy.
  - Good to know if theorists think we succeeded !??
- Analysis & trigger techniques still maturing, with significant improvements from year to year, so expect great things to come!
  - Lots of results based on 2016 data in pipeline.

BACKUP SLIDES

Search for stopped R-hadrons (HSCP) ATLAS (arXiv:1310.6584)

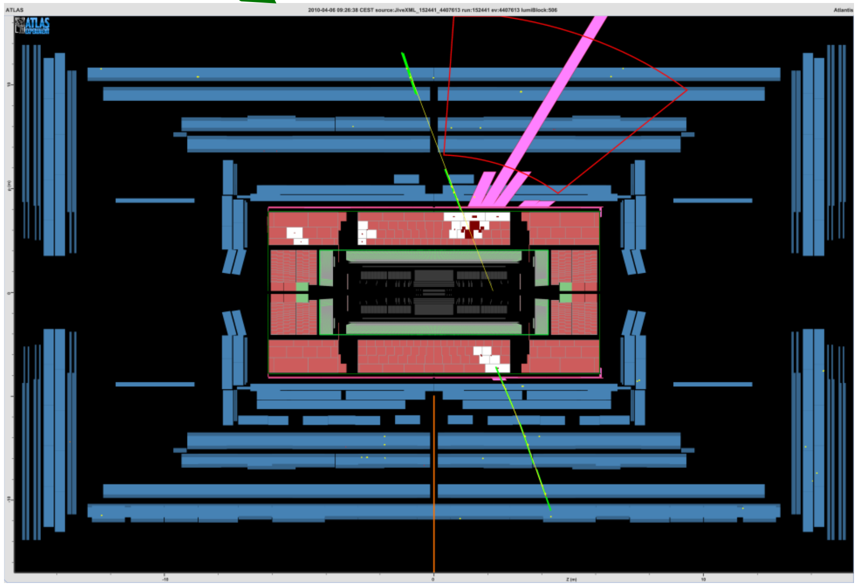
- If R-hadrons are very slowly moving, they lose all their energy through dE/dx, and come to a halt in the calorimeter.

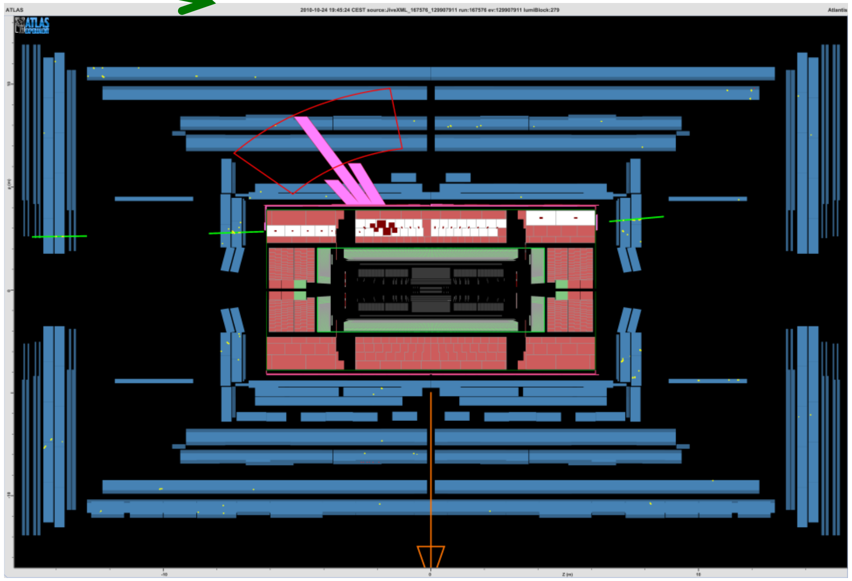


- Search for R-hadrons, produced in LHC collisions, that decay seconds or years later when there is no colliding beam!
- *ATLAS analysis with 8 TeV 2012 data.*

Search for stopped R-hadrons (ATLAS)

- R-hadron decay (e.g., $\tilde{g} \rightarrow g\tilde{\chi}^0$) gives energy deposit in calorimeter.
- So require "jet" + E_T^{miss} at least 125 ns after last pp collision.
- Veto events with muons, to avoid background from interacting cosmics or beam-halo muons.





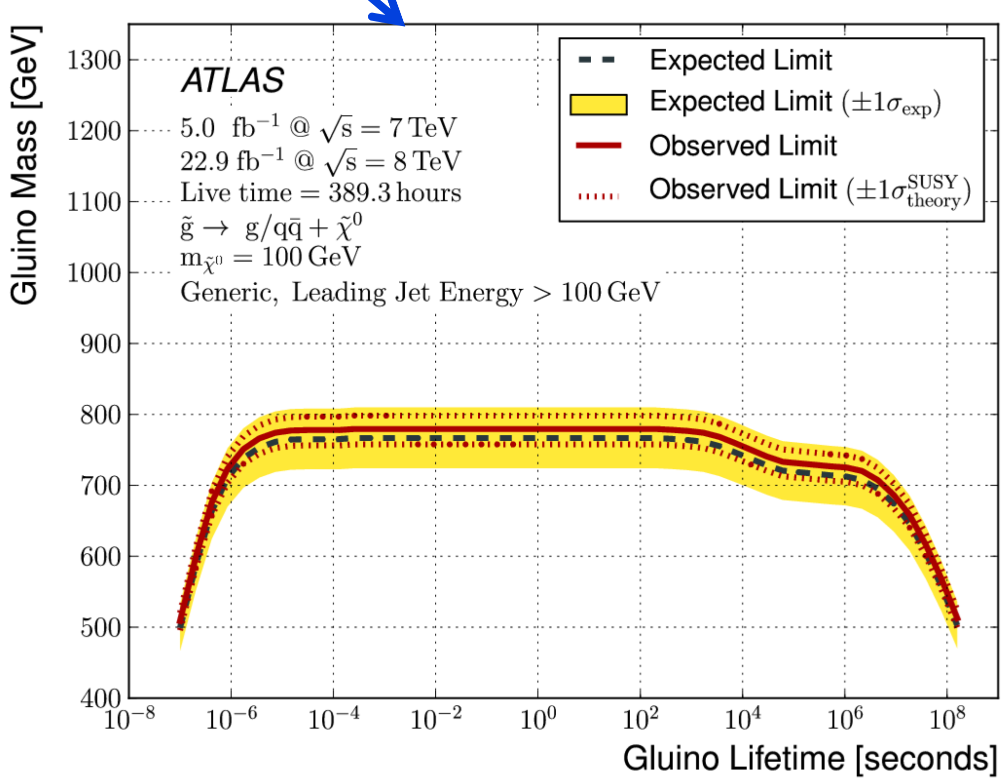
- Cosmic background estimated using data collected before start of LHC data taking!

Search for stopped R-hadrons (ATLAS)

- No events found in 8 TeV data, so limit on gluino mass > 750 GeV for gluino lifetime of 1μs – 1 year.

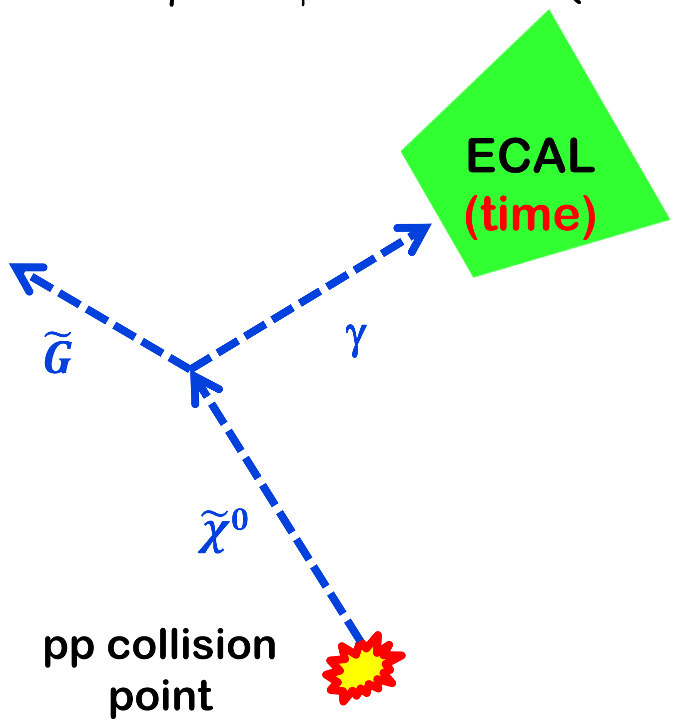
- Rarely competitive with HSCP search, but *very cute* …

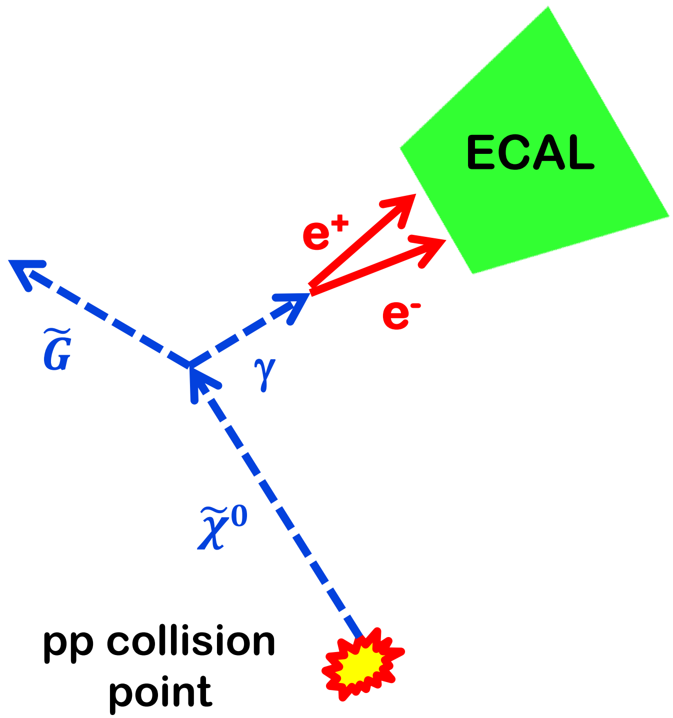
- Similar analysis from CMS (arXiv:1501.05603)



CMS search for long-lived particles decaying to displaced photons
(2 papers: https://cds.cern.ch/record/2063495/ + https://cds.cern.ch/record/2019862/)

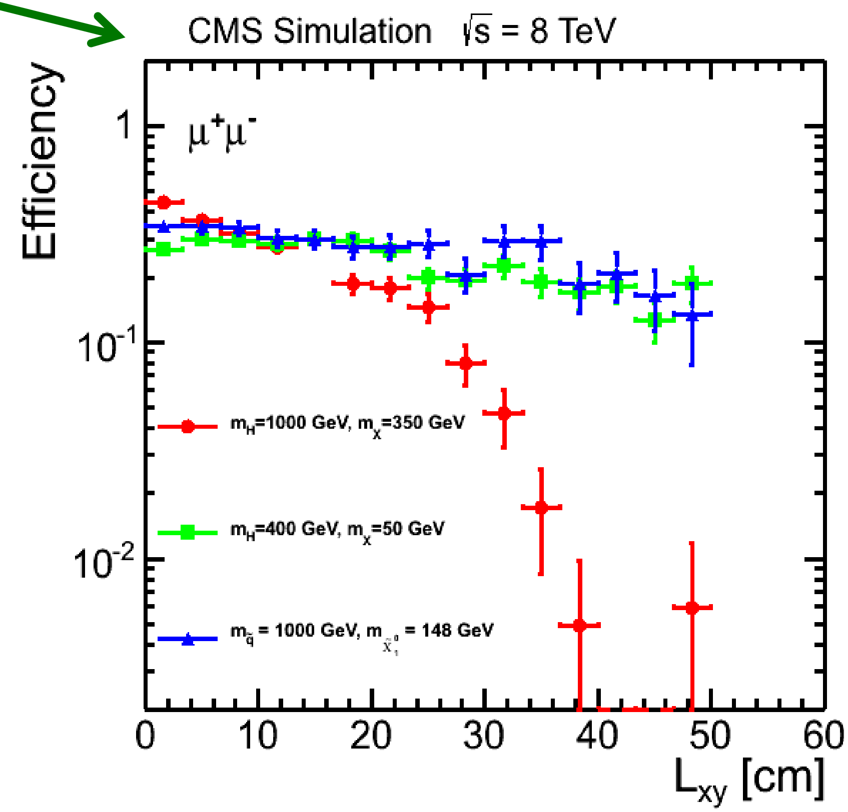
- In GMSB SUSY: long-lived $\tilde{\chi}^0 \rightarrow \gamma\,\tilde{G}$.
- **1st paper** uses ECAL timing resolution (~0.37 ns) to detect late arrival of γ at ECAL (due to indirect path & due to non-relativistic $\tilde{\chi}^0$)
- **2nd paper** profits from large amount of material in tracker (!) to reconstruct γ conversion & hence show that γ trajectory doesn't originate at beam-line.
- Both require E_t^{miss} > 60 GeV (due to $\tilde{G}$).





CMS Search for long-lived particles decaying to displaced leptons
Efficiency

- Decent efficiency for Tracker to reconstruct leptons produced up to 50 cm from beam-line, thanks to effort invested in displaced-track reconstruction.



- (2nd paper didn't fully exploit this, as eμ trigger as was inefficient for very displaced muons.
  -- Will fix in future).

RESULT:

- ➢ 1st paper sees no candidates.
- ➢ 2nd paper sees only a few.

CMS search for long-lived particles decaying to displaced leptons
Model independent limits for e+e- or μ+μ- final state

- Define acceptance region where efficiency "high":
  i.e. Lepton Pt > 26-40 GeV & $|\eta| < 2$ & $L_{xy} < 50$ cm.
- Limits on "σ*BR*acceptance" are ~ independent of model (& even lifetime) !
  - Valid for any model where LL particle decays to (l^+,l^-,anything)!
  - Can be translated to limits on σ*BR if you know the acceptance for your model.